DETERMINATION OF BACKUP ALARM MASKED THRESHOLD IN CONSTRUCTION NOISE

by

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Blacksburg VA

Climb high
Climb far
Your goal the sky
Your aim the star

-inscription on Hopkins Memorial Steps,
Williams College, Williamstown, Massachusetts

DEDICATION

To Uncle (Babamukuru) Lewis Muchenje and Brother (Mukoma) Chamunorwa Muchenje-Mujeri. Although you are gone, you are not forgotten. May your souls rest in peace.

ACKNOWLDGEMENTS

This thesis work would not have been possible without the extraordinary help and enthusiasm of some outstanding individuals. Thanks to my co-advisors Dr. Casali and Dr. Lancaster for giving me the opportunity to embark on this thesis work and their guidance. Thanks also to Dr. Smith-Jackson for her diligence and invaluable contribution. Many thanks to the ISE department and those who participated in the experimental sessions; without them, this thesis would not have been feasible.
Many thanks to my family: Mom, Dad, Simon and Rufaro for their love and support, especially my wife Kim whose patient love enabled me to complete this work.
Lastly, but not least, I give thanks to God almighty who makes all possible.

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(ABSTRACT)

Sound transmission devices have advanced filtering abilities that theoretically protect the ear from harmful Masking noise while amplifying the sounds that need to be heard, such as backup alarms. Therefore, such devices should provide improved signal detection in noise when compared to their passive counterparts. The masked threshold of a vehicular backup alarm was determined for audiometrically normal and non-normal hearers using two types of sound transmission devices and their passive counterparts within pink noise and milling machine noise at intensities of 75, 85, 95 and 105 dBA. Results indicated that the sound transmission devices did not have any statistically significant advantages over the passive devices with respect to masked threshold of a backup alarm. Therefore, it cannot be concluded that these devices offer advantage over similar passive devices with respect to signal detection. Additionally, ratings of comfort and the ability to detect the alarm for each device were gathered. Both scales did not show any significant differences between the two device types.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Action Level: In general industry, the action level is reached if the 8-hour time weighted average (TWA) is greater than or equal to 85 dBA; at this level, a hearing conservation program that requires specific steps, including audiometry and a hearing conservation program, is to be mandated.

Criterion Level: Applies to both general industry and construction; the criterion level is reached if 8-hour TWA is greater than 90 dBA, after which engineering or administrative controls are required to reduce the noise level to 90 dBA or below.

Decibel (dB): A dimensionless unit equal to 10 times the logarithm to the base 10 of the ratio of two values. In occupational noise measurement, decibels are usually measured in terms of sound pressure, and referenced to 20 µPa.

Exchange Rate (ER): the number of dB required to halve or double the allowable exposure duration. For instance, using a 5 dB exchange rate, an individual could be exposed for 8 hours at a constant sound level of 85 dBA, or 4 hours at a constant sound level of 90 dBA, or 16 hours at a constant sound level of 80 dBA.

Frequency: the number of pressure cycles per unit time, usually in cycles per second or Hertz (Hz).

HCP: hearing conservation program.

HPD: hearing protection device; i.e., an earplug or earmuff that is designed to reduce noise exposure at the wearer's ear.

L_{eq}: the average sound level in dBA over any specified time period.

L_{max}: the maximum sound level in dBA over any specified time period.

Masking: the magnitude of the threshold increase of a signal in the presence of Masking noise, measured in dB.

Masked Threshold: the elevated minimum audible level of a sound that is masked.

Noise: any undesirable sound.

NIHL: noise induced hearing loss

NIPTS: noise induced permanent threshold shift

NRR: Noise reduction rating.

PTS: permanent threshold shift

Permissible Exposure Level (PEL): A-weighted sound level at which exposure for a stated time, typically 8 hours, accumulates 100% dose. (PEL also may stand for the protected exposure level, which is the measured intensity of a sound under an HPD.)

Signal Noise Ratio (S/N): the signed difference between the signal level and the Masking noise level

Time Weighted Average (TWA): the non-varying sound level that would produce a given noise dose if an employee were exposed to that sound level continuously over an 8-hour period. Thus, the 'run time' is 8 hours by definition for TWA.

TTS: temporary threshold shift

INTRODUCTION

Construction is one of the most hazardous of industries. In 1998, it was estimated that over 750,000 workers in the construction industry are exposed to hazardous levels of noise, and the most exposed workers are in road construction and in carpentry (Hattis, 1998). Besides the obvious effect of noise-induced hearing loss (NIHL) and communications interference, safety and performance degradations are other adverse effects that noise exposure might have on workers (Suter, 1991). Noise does become a problem when it masks speech or auditory signals that are necessary to carry out the job or ensure employer safety. While other types of methods exist to combat noise exposure, the use of hearing protection devices (HPDs) remains as one of the most viable means of reducing noise exposure. However, an important concern that often arises when one recommends the use of HPDs is what effect they might have on the users' ability to communicate verbally, or to listen for warning signals such as backup alarms.

Greenspan, Moure-Eraso, Wegman, and Oliver (1995) conducted a study in which they observed that, out of a group of road operating engineers and laborers, only one operating engineer, already suffering from hearing loss, wore hearing protection. The study also showed that the majority of these operating engineers were more than 50 years old and had worked in their trades for more than 20 years. Moreover, most of these workers reported that the use of hearing protection interfered with their ability to communicate and to hear signals in noisy environments. Research has concluded that for individuals with normal hearing who are exposed to high noise levels (defined here as greater than 85 dBA), the use of conventional HPDs does not hinder, but may actually enhance, users' ability to hear speech and warning signals (Suter, 1989; Casali, Robinson, Dabney & Gauger, 2004). The theoretical explanation for this is that, at high noise levels and for an unoccluded ear, the cochlea distorts the noise, making it difficult to perceive any signals within the noise (termed cochlear distortion). Conventional HPDs attenuate both signals and noise by the same amount (in dB), and in so doing, they permit the cochlea to respond to stimuli without as much distortion, thus fostering signal detection on the part of the listener. This effect can be paralleled to wearing sun glasses in a bright day, where the glasses reduce the illumination, hence allowing the eye to function in a more relaxed manner (Berger, 1991). This effect, however, will heavily depend upon the type of HPD used, and other factors, such as listeners' hearing ability, thus making way for investigations of various types of HPDs.

Specifically for this study, a particular type of HPD called a 'sound transmission device' was evaluated against its counterpart, passive conventional HPD. Sound transmission devices utilize active electronic circuitry that have the ability to differentiate sounds, such as warning signals (below a specified level—usually 85 dBA), and disallow passage of harmful, high-intensity Masking noise (i.e., those above 85 dBA). In essence, these devices have the ability to block out the harmful, high intensity noise through their passive attenuation qualities and to pass the essential bandwidth of speech and backup alarms using active circuitry. Thus, the purpose of this experimental research was to explore the effectiveness of sound transmission devices in signal detection against their passive counterparts.

BACKGROUND

In any job environment that relies on the use of power machinery for job efficiency and productivity, the adverse effects of noise (e.g., NIHL, temporary threshold shifts [TTS, when hearing levels change after noise exposure], difficulty in detecting signals) from the machinery are to be expected. These noise exposures are a safety and a health issue in many industries. The construction industry remains as one of the most underrepresented industries when compared to other industries that have undergone extensive reviews on noise exposure levels (Suter, 2002). Further, the laws governing construction noise exposure are generally less specific and are less protective than those for general industry or mining, as will be documented later.

Controls

With the prevailing high noise exposure levels that the construction industry faces, various forms of interventions may be applied to help reduce these levels to the worker. As a way to alleviate such exposures, different prevention strategies can be used, which generally fall into one of the three following categories:

1. Engineering controls
2. Administrative controls
3. Personal protective equipment (in this case, HPD)

Engineering controls are considered one of the most effective and best long-term solutions of controlling noise hazards. This is because engineering controls reduce the hazardous noise levels at the source, i.e., not involving the person in any way. The most common types of engineering controls include isolating the machine (e.g., barriers, or absorbers), or redesigning the machine (e.g., by implementing mufflers). However, this is not always feasible, and is often limited. For example, some construction companies rent equipment from equipment suppliers and do not have the freedom to improve them. On the other hand, other on-site equipment may belong to sub-contactors who may not choose to modify them for added noise reduction. Engineering controls are also often too expensive, but in other cases may end up cheaper in the long run (Eaton, 2000).

The second form of control is administrative, which does not necessarily reduce the noise levels, but focuses on reducing exposure time of workers to the dangerous noises. Some of the strategies used for this form of control are rotating workers between noisy and quiet jobs, and taking appropriate rest breaks. Besides the obvious disadvantage of reduced productivity and efficiency, it is not a healthy practice. While job rotation may reduce the amount of hearing loss per individual, doing so may spread the risk among many workers.

The last form of reducing noise exposure levels is through use of personal protective equipment, such as HPDs. Although this form might be the least effective way if not well implemented, it is the most widely used control in both industrial and construction settings. This might be because most of the devices are cheap and are relatively easy to implement. A major difference between a construction setting and a regular industrial setting is that in the former the workers frequently work in rapidly changing work sites with exposure to noise from varying equipment and from the environment that includes traffic external to the worksite, while a factory environment is generally more static with respect to noise and its variability. In addition, construction workers have relatively little control over their environment. Therefore, noise exposure on construction sites is not as amenable to engineering controls as in the manufacturing sector. Construction work involves the use of various tools; most tools produce high noise levels with large variations in the noise levels, resulting in intermittent noise. Suter (2002) summarized some of the noise levels produced by common equipment used in the construction environment (see Table 1).

Table 1. Sound levels in L_{eq} by equipment/tool used (Adapted from Suter, 2002).

Tool name	Tool Drive type	Median dBA	SD dBA	Range dBA
Air compressor	pneumatic	96	11.2	70–114
Backhoe	gasoline	86	6	70–108
Bulldozer	gasoline	89	8.2	70–104
Chipping gun	pneumatic	93	13.1	70–120
Chop saw	electric	80	8.6	70–106
Crane	electric	78	7.7	70–110
Forklift	gasoline	85	5.8	62–125
Hand hammer	mechanical	85	8	56–110
Jackhammer	pneumatic	104	11.4	70–112
Lejeune gun	pneumatic	89	8.4	70–120
Truck	gasoline	78	8	70–123

As shown above, most common construction equipment produce noise levels that are of high intensity, and are well above the 90 dBA 8-hour Time weighted average (TWA). By definition, TWA is the non-varying sound level that would produce a given noise dose if an employee were exposed to that sound level continuously over an 8-hour period, as required by Occupational Safety and Health Administration (OSHA), to be discussed in the following section. There is also a large variation in standard deviation, which is representative of the variation of sound levels for most equipment during operations in the construction environment.

Other sample measurements taken at different road construction sites are indicative of a high noise dose which, by definition, is the percentage representation of exposure level. According to OSHA regulations, no worker should be exposed to more than 90 dBA 8-hour TWA, which is equivalent to a 100% dose. Figure 1 below is a sample of noise doses as measured during road construction operations using various equipment (J.A. Lancaster, personal communication, August 2005). As shown in Figure 1, most construction equipment produces noise doses well above the 50% (OSHA action level) dose limit.

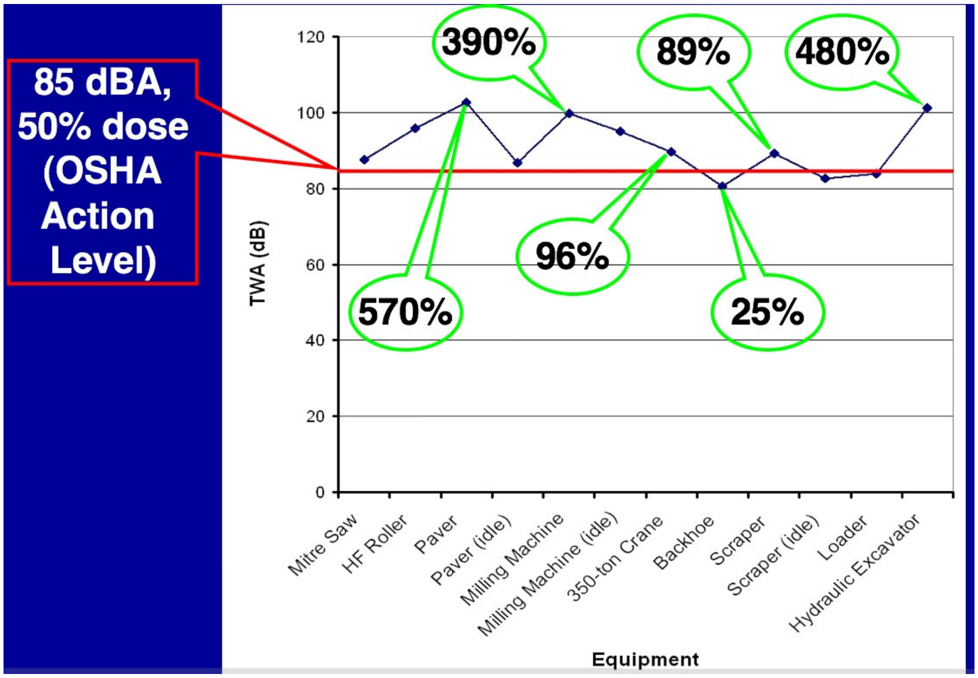

Figure 1. Sound level measurements: TWA and projected. (Adapted from J.A. Lancaster, personal communications, August 2005)

OSHA Regulations

The noise exposure situation is even less favorable for construction workers when one considers that they are not covered by OSHA's hearing conservation amendment (Suter, 1991). There are separate noise regulations in the United States for construction and for general industry. OSHA sets permissible exposure limits (PEL) against health effects to hazardous noise levels.

The first protective legislation addressing permissible noise exposure levels was enacted almost 40 years ago with passage of the Walsh-Healey Public Contracts Act of 1969 (shortly before OSHA came into being). This act applied only to employees contracting with the United States government. The act specified a maximum Permissible Exposure Level (PEL) of 90 dBA per 8-hour day with a 5 dB exchange rate. In essence, the 5 dB exchange rate is a way to halve or double the allowable exposure duration for every 5 dB. For instance, an individual could be exposed for 8 hours at a constant sound level of 85 dBA, or 4 hours at a constant sound level of 90 dBA, or 16 hours at a constant sound level of 80 dBA. Any levels above the PEL required engineering or administrative controls. This act included only one sentence about hearing conservation programs.

In 1971 (Code of Federal Regulations [CFR, 1971]), OSHA mandated this law to be applied to general industry and the construction industry, and was termed The Department of Labor Occupational Safety and Health Act, Occupational Noise Exposure Standard.

In 1983 (CFR, 1983), OSHA passed the Hearing Conservation Amendment, which served to supplement the OSHA 1971 standard. The amendment required specific steps for a hearing conservation program (HCP), including audiometry and hearing protection to be worn when the 8-hour TWA reaches an "action level" of 85 dBA TWA, with a 5 dB exchange rate — *but only for general industry*. Administrative controls are to be implemented if noise levels exceed those shown in Table 2 below. If such controls fail, personal protective equipment shall be used to reduce the sound level to within the levels of Table 2.

Table 2. Permissible Noise Exposure**.**

Duration per day, hours	**Sound Level dBA slow response**
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
0.25	115

Note that this regulation imposes the following general criteria:

1) PEL of 90 dBA TWA with a 5 dB exchange rate per 8-hour day. (90 dBA TWA corresponds to 100% dose.) This is called the <u>OSHA criterion level</u>.

2) No [continuous] exposure allowed above 115 dBA. A sound is considered continuous if the variations in noise level involve maxima at intervals of 1 second or less.

3) No impulsive or impact exposure allowed above 140 dB peak sound pressure level (requires special true peak meter measurement capabilities).

4) The exposure allowance (level by duration combination) is always referenced to an 8-hour criterion, regardless of the actual work shift length. The maximum allowed is always 8 hours at 90 dBA TWA. If the work shift exceeds 8 hours, the allowable exposure level must be reduced according to the 5-dB exchange relationship.

The 1983 Hearing Conservation Amendment mandated a hearing conservation program (HCP) to be administered whenever employee noise exposure is greater than 85 dBA (TWA) (slow meter response). This corresponds to a 50% noise dose and is called the OSHA "criterion level." The HCP at levels above 85 dBA consists of specific steps that include:

1) <u>Exposure monitoring</u>- identifying employees in HCP and to enable hearing protector selection. This takes into account issues such as worker movement, noise level variation, and proper selection of HPD

2) <u>Employee Notification</u>- of exposure level.

3) Observation of monitoring- employee may observe the measurement of the noise if desired; annual audiogram required thereafter.
4) Audiometric (pure tone) testing- carried out by an audiologist, M.D. or certified technician. A baseline audiogram is established within 6 months of first exposure. The audiograms are evaluated by comparing to the baseline audiogram with subsequent ones. If an average of 10 dB elevation of threshold ('standard threshold shift' or STS) from baseline (at 2000, 3000, 4000 Hz in either ear) occurs — the employee is informed and action is taken; also, a presbycusis correction (i.e., age-related hearing loss) may be applied to the threshold shift.
5) Hearing protectors- must be made available if TWA exceeds 85 dBA.
6) Hearing protector attenuation-Protectors shall reduce exposure to less than 90 dBA TWA, and to 85 dBA TWA for employees with a STS. The protectors' adequacy shall be evaluated according to one of the methods stated in appendix B of the OSHA standard.
7) Training program- Training concerning effects of noise on hearing, use of HPDs, and the purpose of audiometric testing will be provided annually.
8) Access to information and material training- employee will be provided with OSHA standard information and the employer will provide OSHA with the training material used.

Record keeping- This includes a record of exposure measurement noise data, record of audiograms for duration of employment, record of audiometer calibration and test room noise measurement. The records are also transferable in the event that the business is sold (Adapted from Casali 2005c).

In contrast, construction workers are not covered by this regulation; they are covered only by the 1971 regulation that limits the exposure limit to 8-hour TWAs of 90 dBA or less. Above these levels, engineering and administrative controls are required to reduce such noises to 90 dBA or below.

Even with the 1971 regulation, which is less complete, its enforcement in the construction industry is often not rigorous. For example, in 1998 only 63 noise related inspections were conducted and 79 citations given out of the over 18,000 federal construction inspections during that year (OSHAa). This suggests a lack of enforcement for both noise reduction and noise conservation in the construction environment. It is not difficult to see how construction workers suffer as a result.

Dosimetry data with an 8-hour TWA and 5 dBA trading relationship (exchange rate) were obtained at a road construction site to analyze noise intensities and exposures for workers (see Figure 2). It is evident that the Figure depicts the severe noise levels produced by these equipment (J.A. Lancaster, personal communication, August 2005). It is apparent that most of the equipment that is used in road construction produces noise levels that are well above the 85 dBA OSHA "action" level.

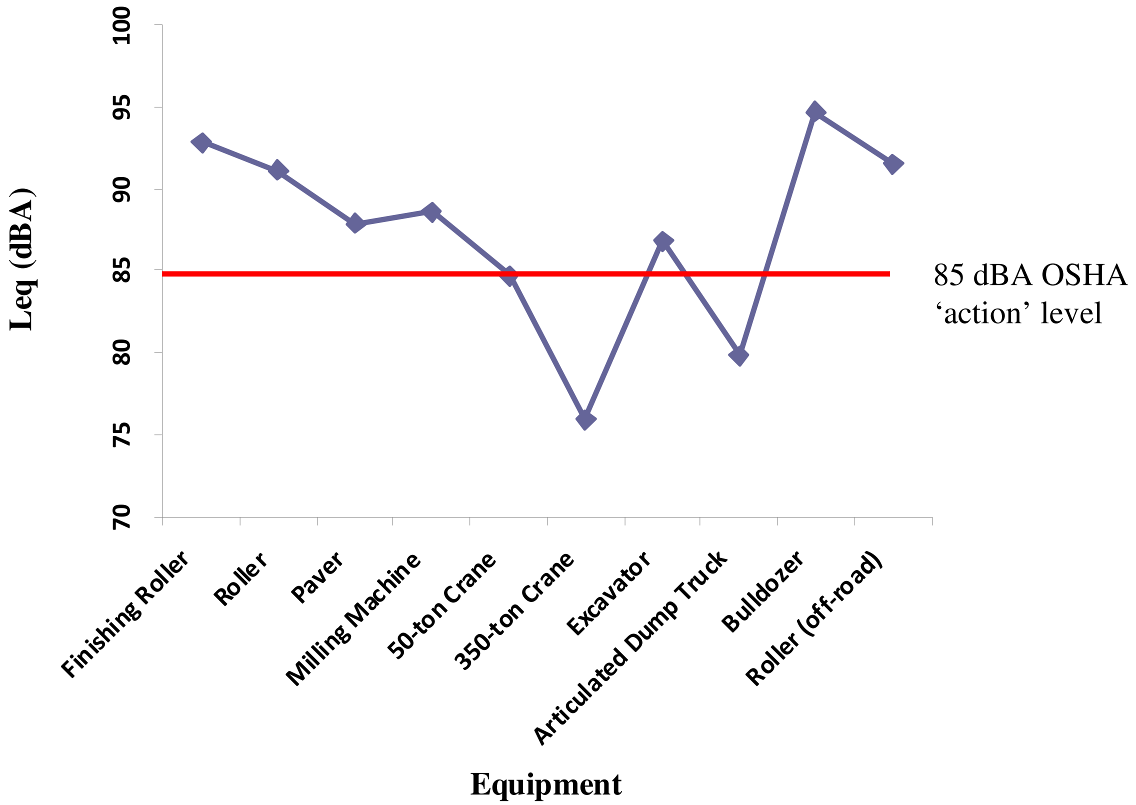

Figure 2. Noise levels (8-hour TWA) produced by a sample of construction equipment. Most equipment produces noise levels above the 85 dBA OSHA 'action' level, indicated by red line.

Noise Induced Hearing Loss (NIHL)

The obvious effect of noise exposure is noise induced hearing loss (NIHL), which is the second most prevalent form of sensorineural hearing deficit after presbycusis, which will be described later in this section. Shearing forces that are caused by sound have an impact on the hair cells on the basilar membrane of the cochlea. When excessive, these forces can cause cell death (Rabinowitz, 2000). Previous studies have revealed that more than 9.2 million U.S workers are exposed to noise levels above 95 dBA TWA per 8-hour day, and more than 5.5 million of these are in general industry and maritime operations (EPA, 1981). Regrettably, the OSHA hearing conservation amendment, described earlier (EPA, 1981), does not cover most of these workers.

NIHL is an insidious condition, that can take years to develop to a stage where it affects an individual's ability to communicate at home and in the workplace. Most hearing loss begins as a temporary condition, known as *temporary threshold shift* (TTS). TTS represents transient hair cell dysfunction and normally occurs when an individual is exposed to excessive noise (e.g., at a rock concert) (Rabinowitz, 2000). Repeated TTS may ultimately cause a permanent hearing deficit, also known as permanent threshold shift (PTS). Figure 3 shows noise induced permanent threshold shift (NIPTS) data as a function of exposure time for typical industrial work (at least at the time, jute weaving). The characteristic (frequency at which NIHL is first typically seen) 4 000 Hz notch is evident; the notch gets wider as exposure time increases. An individual suffering form NIHL would probably have difficulties in perceiving alarm signals such as a backup alarm, which has its peak frequency and harmonics at 1250 Hz and 2500 Hz, respectively. This is due to fact that a person suffering form NIHL tends to lose their hearing first in the 1-4 KHz frequency range, which is inclusive of the backup alarm peak frequency (i.e., 1250 Hz).

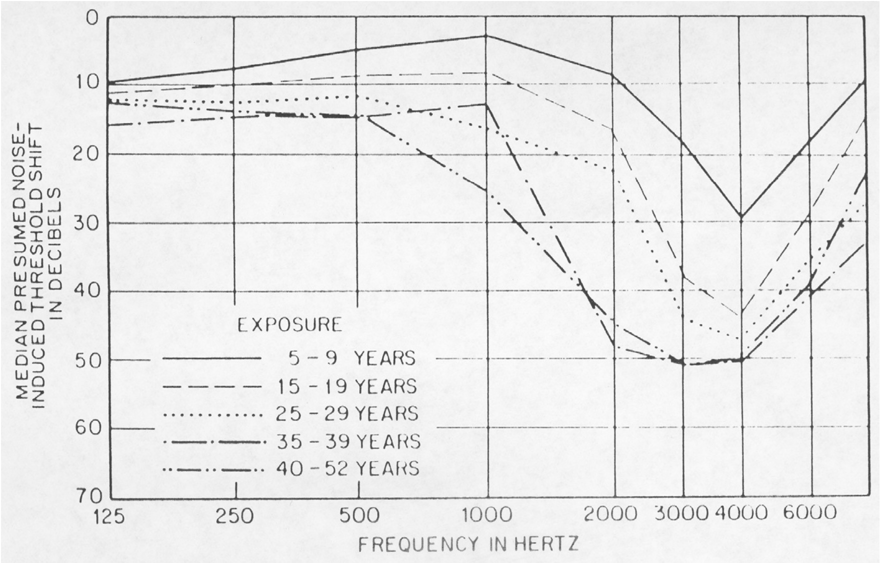

Figure 3. NIPTS as a function of years of occupational exposure in jute weaving (Taylor et al., 1964, as in Casali, 2005b).

One of the most striking results indicating a PTS was that of a seventy-three year-old male bulldozer operator, whose audiogram is shown in Figure 4 below (J .A Lancaster, personal communication, August 2005). The pre-workday audiogram for the bulldozer operator is shown superimposed on a graph of hearing levels for non-noised exposed males over 60 years of age (OSHA 1910.95, Appendix F). This was done for comparative purposes to see if the bulldozer operator exhibited hearing levels worse than would be expected for non-noise exposed males over sixty years of age. Clearly, the graph confirms this as there is a large difference in hearing levels at all frequencies between the bulldozer operator and that which would be expected for non-noise exposed males of his age.

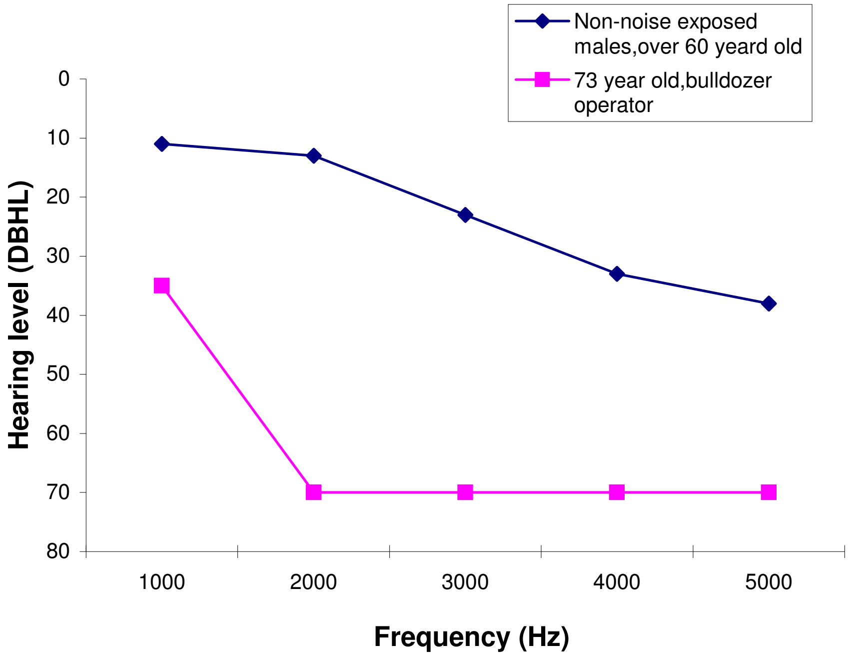

Figure 4. Permanent threshold shift suffered by a 73 year-old bulldozer operator. Comparison with age-corrected hearing levels, this worker has suffered extreme hearing loss over his 45 years in the construction industry. (Data for Non-noise exposed males over 60 was adapted from OSHA 1910.95 Appendix F)

Occupational noise is not the only common cause of hearing loss in a noisy environment-- there are also other types of hearing loss that can occur. One common type that was mentioned earlier is called presbycusis (Figure 5).

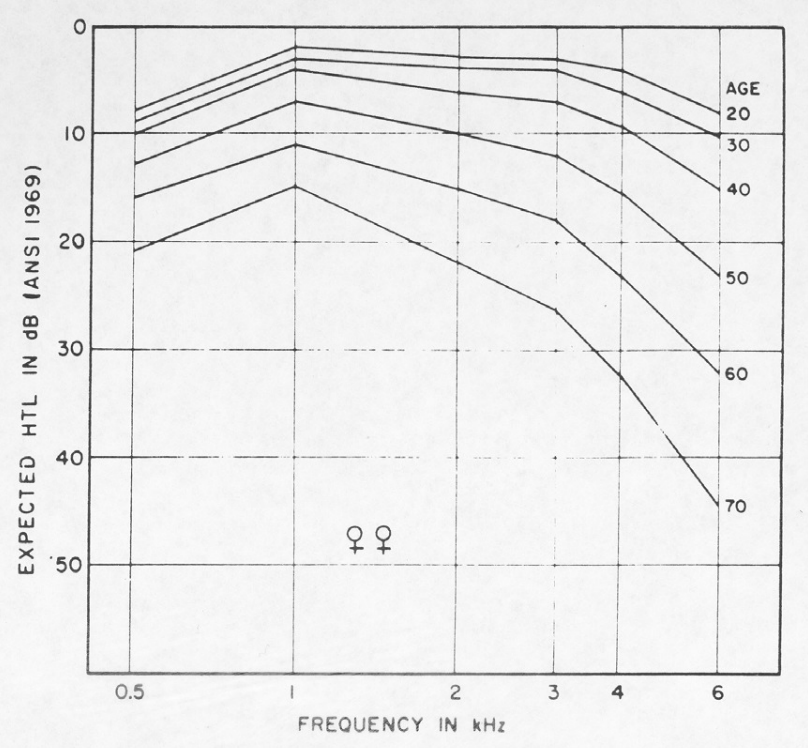

Figure 5. Presbycusis: Expected Hearing Levels in an industrialized society for non-noise-exposed females (age corrections after Spoor, 1967 added to median Hearing loss of 20 year-old non noise-exposed, as in Casali, 2005b)

Unlike NIHL, this type of hearing loss does not have the characteristic 4 KHz notch; instead, it tends to affect the high frequencies more, as shown by the declining hearing threshold lines at the 3-6 KHz frequencies in Figure 5. Consequently, this condition would be less likely to present an adverse effect on a person's ability to detect a backup alarm frequency with peak frequency at 1250 Hz, as in the previous case with NIHL.

The existence of NIHL in the construction industry in other parts of the world has been documented by earlier studies. For instance, the Ministry of Labor in Japan estimated that 16% of Japanese construction workers suffer from NIHL (Miyakita and Uenda, 1997). The worker's compensation law in Germany, which was designed to ensure that employees who are injured or disabled on the job get monetary awards, found NIHL as one of the most common occupational related illnesses in Germany's construction industry (Arndt, Rothenbacher, Brenner, Fraisse, Zschenderlein, Daniel, Schuberth, & Fliedner, 1996). Finland also recorded an NIHL incidence of 30 cases per 10,000 construction workers; this number is likely low due to many other unreported cases (Welch & Rota, 1995). In the US, several millions of dollars are paid out each year by several companies to compensate individuals who suffer from NIHL (Dobie, 1995).

HEARING PROTECTION DEVICES AND ELECTRONIC AUGMENTATIONS THEREOF

When administrative or engineering controls are not feasible with respect to noise exposure, the only alternative is personal protective equipment in the form of HPDs. These devices typically come in the form of earplugs or earmuffs. However, other technologies exist that help to reduce noise levels at the ear, including active noise reduction (ANR) and amplitude-sensitive devices. Each of these is discussed in turn below.

Passive Devices

Passive HPDs, sometimes called *conventional* HPDs, can be broadly categorized into earplugs, earmuffs, and semi-aural devices. These three categories are discussed in the passages that follow. There is no consideration on elevating the levels of speech intelligibility and signal detection under these HPDs. Conventional HPDs function by physically blocking the air conduction pathway to the listeners' inner ear (Casali and Robinson, 2002). In such cases they tend to attenuate *both* desirable and undesirable sounds equally.

Earmuffs. All earmuffs consist of two cups that are connected by a headband or are attached to a hardhat, as shown in Figure 6. They are worn such that the two cups cover the ears and form a seal against the side of the head. The headband compresses the cushion, aiding in establishing a seal. Earmuffs are the most common form of hearing protector on the market today. Their primary purpose is to reduce noise exposure to the user. Design parameters such as cup volume, cup mass, headband force, surface area of the opening in the cushion, and the material from which the device is constructed affect their attenuation characteristics (Berger, 2000). Earmuffs tend to attenuate high frequency noise better than earplugs, while earplugs attenuate low frequency better than earmuffs. This is mainly due to the physical design of the earmuff, specifically the size and weight of the muff. There are 3 main ways that sound can bypass the muff and enter the ear canal:

- **Leakage –** sound waves move around the earmuff, entering through gaps in the ear cushion seal
- **Penetration** – sound that transmits directly through the shell of an earmuff
- **Vibration** – movement or subtle shaking of the earmuff as a whole

It is therefore challenging for earmuff designers to minimize these three pathways of sound (especially low frequency sounds) entering the ear canal without increasing the earmuff's size or weight. The attenuation for plugs vs. muffs is illustrated in Figure 7.

Figure 6. Typical example of passive earmuffs.

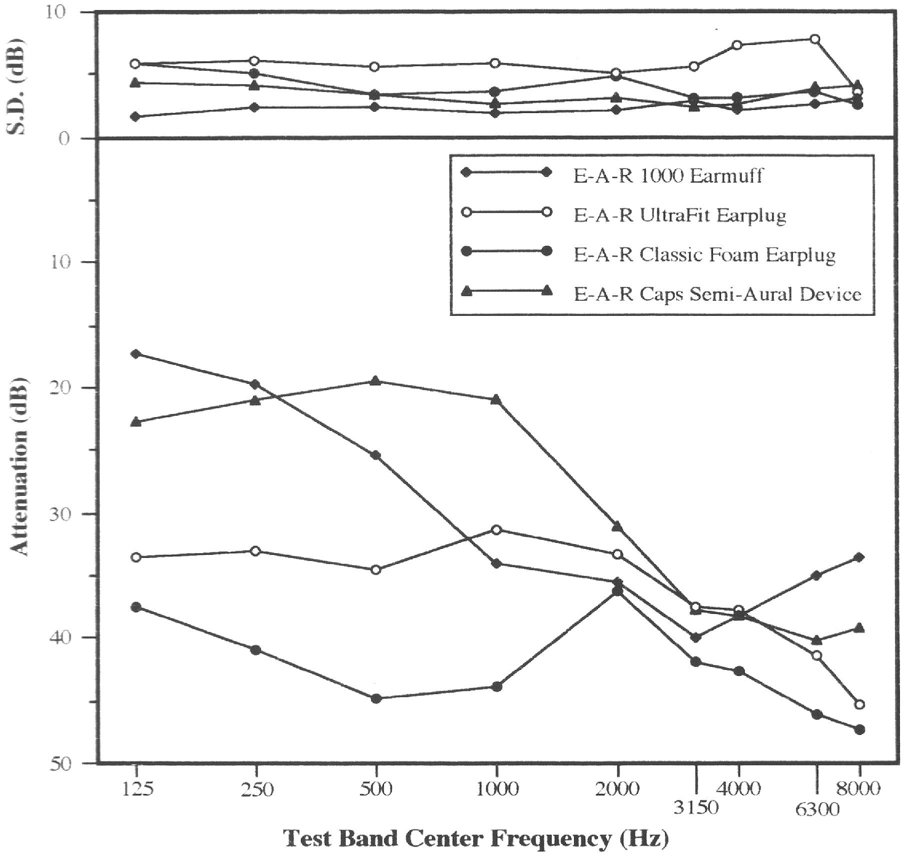

Figure 7. Comparison of the attenuation characteristics of an earmuff, two earplugs and a semi-aural device. (Adapted from Robinson, 1993)

Earmuffs are good for intermittent noise exposures due to their donning and doffing easiness, which is one advantage that they have over earplugs. Their size and external visibility also makes it easier for supervisors to monitor their use by employees. However, for long-term periods, earmuffs are often reported to feel tight, hot, bulky and heavy, although their warming effect can be appreciated in cold environments (Berger, 2000). Other disadvantages they have over earplugs are that their fit tend to be affected by the head and jaw shape of the user, the presence of facial hair, and the use of other personal protective equipment such as safety glasses, hardhats, and respirators, which may impact the earmuff's seal.

Earmuffs do have a large enough structure such that electronic augmentation, such as transmission circuitry can easily be adapted to them. These augmentations are discussed later. Studies have been done to investigate the hearing of signals (e.g., back up alarm) under these HPDs, these studies are described in the signal detection sections.

Earplugs. Earplugs are worn by inserting them into the user's ear canal. As noted previously, they tend to attenuate low frequencies better than earmuffs, and are not significantly affected by the use of other personal protective equipment such as safety glasses and hardhats. Earplugs, in general, are available with or without a lanyard connection cord, or flexible head or neckbands; in the latter case, they are called "canal caps" or "semi- aural" devices. Both cords and bands prevent them from being misplaced and, simplify storage by permitting the wearer to drape them around the neck while not in use (Berger 2002). They do, however, have disadvantages in comparison to earmuffs. For example, earplugs tend to consume more time and effort to don and doff than earmuffs. More importantly, in typical construction environment, the dust and dirt present in the atmosphere can become imbedded in the plug (especially 'foam' plugs) resulting in possible hygiene problems (Suter, 2002).

Earplugs can be grouped into the following design categories: pre-molded, user-molded, or custom-molded; each of these is discussed below.

- <u>Pre-molded earplugs</u> are manufactured from flexible materials such as vinyl or cured silicon, and are shaped conically, are bulbous, or are in other forms, as shown in Figure 8. Silicone formulation tends to offer the best durability and resistance to shrinkage (Berger, 1991). They often have flanges (from zero to five) or sealing rings to aid in creating an effective seal. They are also available in different size ranges to fit most ears. These plugs do not require 'roll down,' which is a process of compressing the plug prior to insertion (e.g., foam earplugs). This is an advantage for those with limited dexterity who may have difficulty in achieving roll down. Silicone formulation also promotes potential hygienic benefits over foam earplugs, such as in cases were roll downs must be accomplished with filthy hands (Berger, 2002).

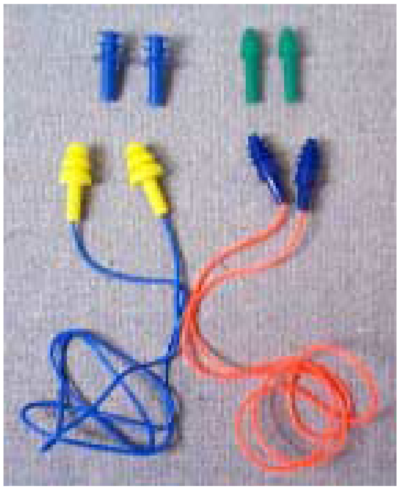

Figure 8. Typical example of pre-molded earplugs.

- User-molded earplugs are made from malleable materials such as foam (the most common type), cotton/wax combination, non-hardening silicon putty, or fiberglass (Figure 9). These plugs are designed to mold themselves into the user's ear canal shape, and their variation in shape and size is less problematic than the pre-molded earplugs. Cotton, by itself, is a poor hearing protector due to its low density and high porosity (Berger, 2002), but when combined with wax, it provides some attenuation. Unlike the pre-molded and custom-molded earplugs, these devices cannot be cleaned; hence, they require constant replacement.

Figure 9. Typical example of user-molded earplugs.

- <u>Custom-molded earplugs</u> are mostly manufactured from silicon putties, vinyl, or acrylics, all of which hold their shape after curing (Figure 10). They are made by obtaining an impression of the user's ear canal and producing an earplug that exactly matches the impression. Custom-molded earplugs are therefore user-specific and are designed to fit only one ear canal. This can be an advantage in that it provides an incentive for motivating employees to wear their HPDs (Berger, 2002); further, they are also less likely to be fitted improperly. One main disadvantage is that their fit is affected by the user's change of body weight (Berger, 2002). Custom-molded earplugs are sometimes used as bases for housing communication features or other augmentation, in the same manner as earmuffs.

Figure 10. Typical example of custom-molded earplugs.

Semi-aural devices. Semi-aural devices, also termed canal caps, concha-seated, or banded earplugs, consist of a headband that holds them in place (shown in Figure 11). These devices' headbands can either be worn under the chin or over the head, and their fit is usually not compromised by safety glasses or hardhats. Another advantage is that they are very easy to don and doff (hence they are often used in intermittent noise), but workers often find them uncomfortable (Park and Casali, 1991) and dislike their effect on the perception of their own voices due to the "occlusion effect" they sometimes generate (Suter, 2002). This occlusion effect is caused by fact that they tend to cap the ear canal at or near its entrance.

Figure 11. Typical example of semi-aural devices.

Active Devices

Amplitude-sensitive devices. Amplitude-sensitive transmission devices (also called assistive-listening or sound transmission devices) are electronically augmented devices, typically earmuff based, incorporating a microphone and an output-limiting amplifier to transmit external sounds to earphones mounted within earcups (Casali, 2005a). The active electronic circuitry in these devices has the ability to differentiate signals, such as speech and warning signals, from other harmful Masking noise (Casali, 2005a). Essentially, these systems maintain the ability to block out the harmful high intensity noise (by using passive attenuation qualities) and pass essential bandwidth such as those of speech and back up alarms (using active circuitry in low noise levels) through its earcups to the wearer's ears. These systems provide reduced "attenuation" at low levels (i.e., when the pass-through is active) and increased protection at high noise levels (i.e., when the pass-through circuitry shuts off). This effect will be fully described later on specific sound transmission devices utilizing an acoustical test fixture ([ATF], per ANSI S12.42-1995). The signal may be filtered to pass only a narrow band of frequencies (such as the speech bandwidth, which is between 1000–4000 Hz) (Casali, 2005a). The signal of the amplifier may be adjusted, but usually to a maximum output level of about 85 dBA and below (the OSHA limit). The limiting amplifier typically maintains a predetermined (in some cases user-adjustable) gain, often limiting the output to about 82-85 dBA, unless the ambient noise reaches a cutoff level of 115 to 120 dBA (as illustrated in Figure 12), and they have similar behavior to a conventional HPD at these high noise levels (Casali, 2005a; Casali and Robinson, 2002). Auditory perception and noise level under such devices may depend upon factors such as cutoff sound level and the sharpness of attenuation transition at that level, system response delay, frequency response and bandwidth, distortion and residual electronic noise, signal/noise ratio at sound levels below the cutoff, and sensitivity to wind effects (Berger, 2000)

Microphone designs for the electronic sound transmission HPDs maybe *diotic*, a case whereby a single microphone on one earcup feeds both earphones, or *dichotic*, whereby each earcup has a separate microphone, hence different signals are presented to each earcup. The dichotic design provides better localization abilities to the user in cases where sound localization is important (Berger, 2002). This contention provides the basis for some of the experimental hypotheses presented below.

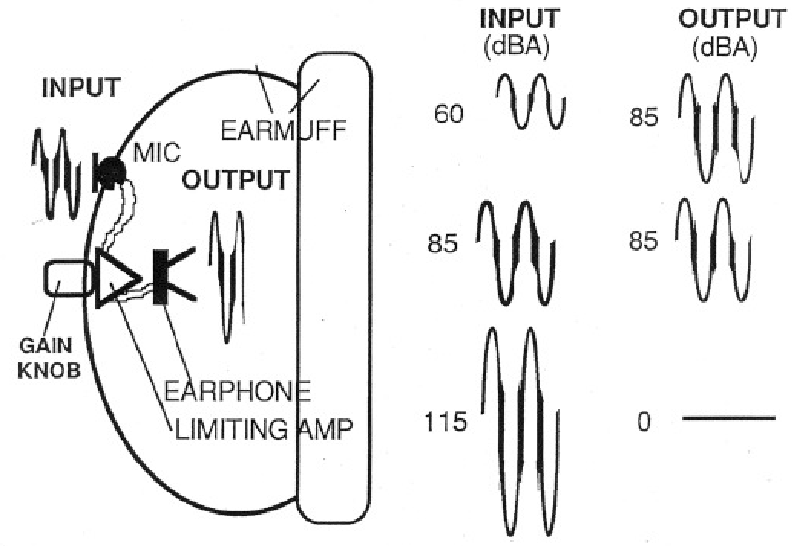

Figure 12. Functional characteristics of electronic sound transmission devices (Adapted from Casali, 2005a).

Active noise reduction (ANR) devices In theory, ANR electronics rely upon the principle of *destructive interference* to cancel the noise. Basically, a 180° out-of-phase signal, of equal amplitude to the noise at issue, is created. This out-of-phase signal counteracts the original noise, causing energy cancellation (Berger, 2000). Figure 13 illustrates this process of cancellation.

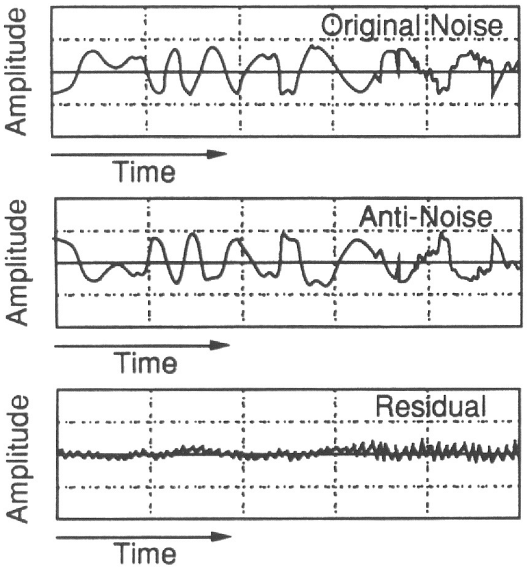

Figure 13. The processes of active noise cancellation (Adapted from Christian, 1999).

A block diagram showing the typical components of an analog electronics, feedback-type muff-based ANR HPD appears in Figure 14. The Figure illustrates a closed-loop, "feedback system which receives input from sensing a microphone that detects the noise which has penetrated the passive barriers created by the earmuff. The signal is then fed back through a phase compensation filter which reverses the phase, to an amplifier which provides the necessary gain, and finally is an output, as an *anti-noise* signal" (Casali, 2005a).

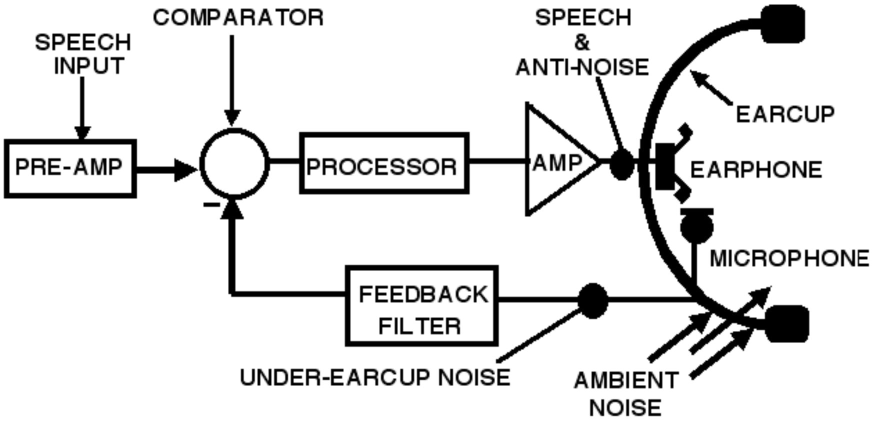

Figure 14. Block diagram of an analog, feedback-type active noise reduction earmuff with speech unit. (Adapted from Casali, 2005a)

ANR devices are most effective against repetitive or continuous noise that does not vary too greatly in spectrum over time. This allows the system to stabilize the phase and amplitude parameters needed for cancellation. They have greater attenuation abilities in the low frequencies, whereas at high frequencies, the waves will be more out of phase, resulting in less attenuation. However, ANR devices are plagued with residual noise artifacts that typically appear at or near 1000 Hz. These residual noise levels may be due to the fact that the anti-phase signal might have a slight time lag from the original noise signal (Christian, 1999).

The total attenuation of this device is the sum of attenuation from the *active component* (electronic cancellation) and the *passive component* (cancellation due the physical characteristics of the device); this is shown in Figure 15. However, there exists no Environmental Protection Agency (EPA) standardized methods to evaluate the attenuation of these devices due to the active component, which is the main reason why ANR devices cannot be legally marketed in the USA as HPDs—instead, they are generally marketed as noise annoyance-reduction devices or communication headsets for use in aircraft (Perala, unpublished doctoral dissertation).

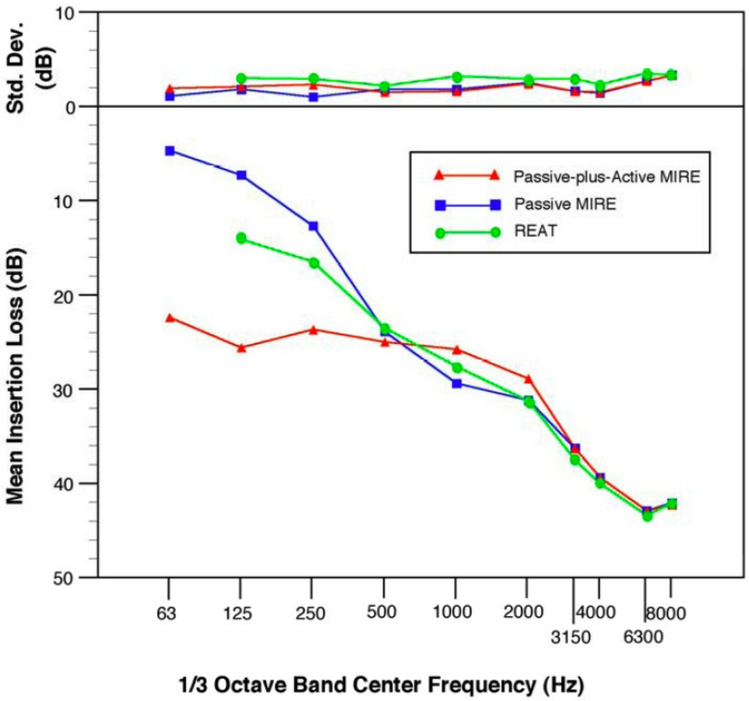

Figure 15. Spectral attenuation of a typical closed-back ANR headset (Adapted from Casali 2005a).

The typical *psychophysical* real-ear attenuation at threshold (REAT) and physical microphone-in-ear (MIRE) attenuation data for a closed-back circumaural ANR muff are shown in Figure 15 above. Apparent in the figure is the difference between MIRE and REAT at 125 and 250 Hz. This difference is due to physiological noise masking of the test stimulus during REAT test (Casali, 2005a)

Which Device is Most Promising for Construction?

As mentioned earlier, conventional HPDs provide attenuation by reducing the intensity of both noise and signals that reach the ear by the same amount. In such cases, the ability to detect desired signals, such as backup alarms, is compromised in environments that are characterized by intermittent noise, such as in the construction industry. That is, an alarm that is easily detected within a lower noise level may not be easily detected as the noise becomes more intense. Therefore, a technology is needed that will amplify desired signals to a level that can be heard, but one that will also protect the worker's hearing within intermittent, high-intensity noise conditions. A promising technology to meet this need is that of the sound transmission device.

The Need for Hearing Signals

Serious accidents occur in noisy workplaces because the signals are not heard. There have been many reports of workers who had clothes or hands caught up in machinery and have been seriously injured while coworkers were unaware of cries of help. There are also other cases were workers, because they were unable to hear the warning alarm, remained on the job while others evacuated (Suter, 1991).

As discussed and illustrated earlier in both Figures 1 and 2, the construction industry is often characterized by high noise levels produced by construction equipment, and from ambient noise (e.g., from cars passing by in the case of road construction). In such an environment, there is a need for safety alarms. A typical alarm found in the construction industry is the backup alarm which sounds whenever a truck, bulldozer, forklift, or other construction vehicle is reversing. OSHA (2000) regulations state that "No employer shall use any motor vehicle equipment having an obstructed view unless: (b) (4) (i) the vehicle has reverse signal alarm audible above the surrounding noise level or: (b) (4) (ii) the vehicle is backed up only when the observer signals that it is safe to do so" (Part 1926.601[b][4]).

The Mining Safety and Health Administration (MSHA) reports that an average of thirteen miners are killed each year by being run over by moving mining equipment. These accidents frequently involve large dump trucks that drive over other smaller vehicles or a worker that is in a blind spot of the truck (Mowrey, nd).

On15 September 2005, a local paper (*The Roanoke times*) reported a case of a public works employee who was run over by a dump truck and killed while working on the road. By all accounts, the worker was unable to hear the backup alarm of the truck, because if he had, from a safety standpoint, the accident may not have happened. There seems to be sufficient evidence to support the contention that the high Masking noises that are prominent in most work environments mask alarm signals, hence increasing the difficulty of perceiving these alarms, and ultimately increasing the rate of accidents.

Five- minute ambient noise measurements were taken at one particular road construction site (J.A. Lancaster, personal communication, August 2005) along with a 1995 Mack dump truck and its enunciating backup alarm. As seen in Figure 16, the alarm signal is masked i.e., backup alarm presented at a lower level than the present ambient noise, this phenomenon is fully described in the following section. The difference between the signal intensity and the noise intensity, termed the signal-to-noise ratio (S/N, fully discussed in the S/N section) is less than 15 dBA, even at the peak frequency (1250 Hz) of this particular backup alarm. Clearly, it would be difficult for a worker to perceive a backup alarm in such an environment.

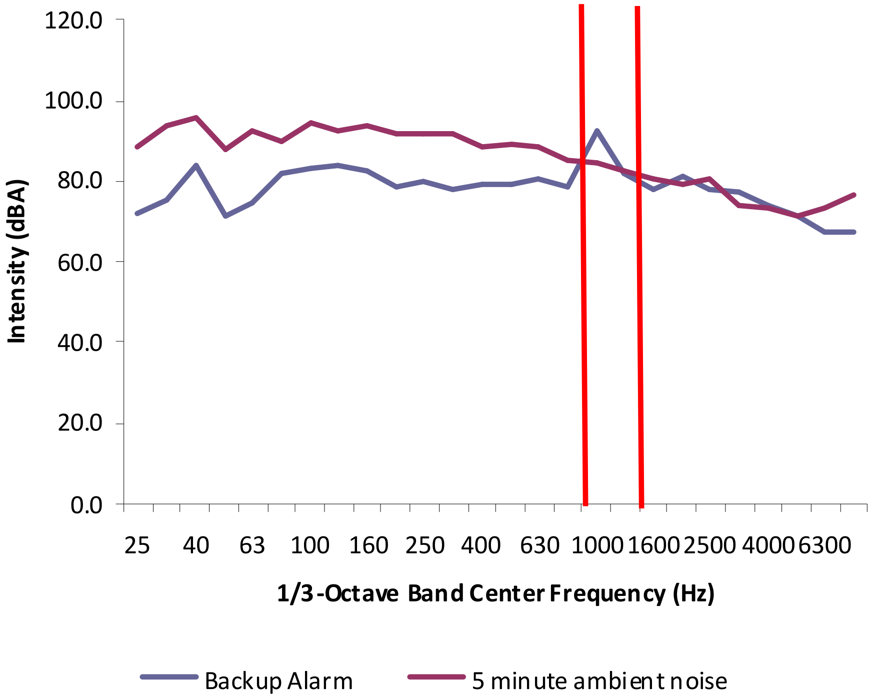

Figure 16. Ambient noise and the backup alarm of a 1995 Mack dump (from approximately 100 feet away as backing towards analyzer). The red lines represent dominant frequency range for a backup alarm.

MASKING

In noisy environments such as in construction, an auditory signal has to be presented at a higher sound pressure level (SPL) than in a quiet environment for it to be heard by the workers in the vicinity. This is because the condition of one sound (in this case, the noise) *reduces the sensitivity of the ear to the other sound* (the auditory signal). This is due to a phenomenon called *masking*, which can be defined as the amount by which the absolute threshold of a sound (masked sound) is raised in the presence of another sound (masking sound). Three basic principles of masking are discussed below.

Pure Tone Masking

Pure tone masking occurs when a tonal signal (i.e., a single frequency) is masked by another tonal noise (the masking tone). In this case, the masking effect is greatest for frequencies around those of the masking tone and its harmonics. At the frequency of the masking tone, a phenomenon referred to as 'beats' occurs: beats are simple tonal interactions with periodic variations in amplitude that result from the superposition of two simple harmonic waveforms with precisely the same frequency. In this case, they are created when the two pure tones (masked tone and masking tone) have *precisely* the same frequency, making it easier for the listener to detect the presence of the tonal signal. In pure tone masking, upward masking also occurs. This is a phenomenon wherein the low-frequency tones produce a masking effect on higher frequency tones, which depends upon the intensity of the masking noise (Casali, 2005b).

Wegel and Lane (1924) clearly illustrated the principle of the upward spread of masking of pure tones; they concluded that the upward spread of masking from low frequency sounds may completely obliterate higher frequencies of considerable intensity, but the reverse does not happen. An example of such a phenomenon is illustrated in Figure 17.

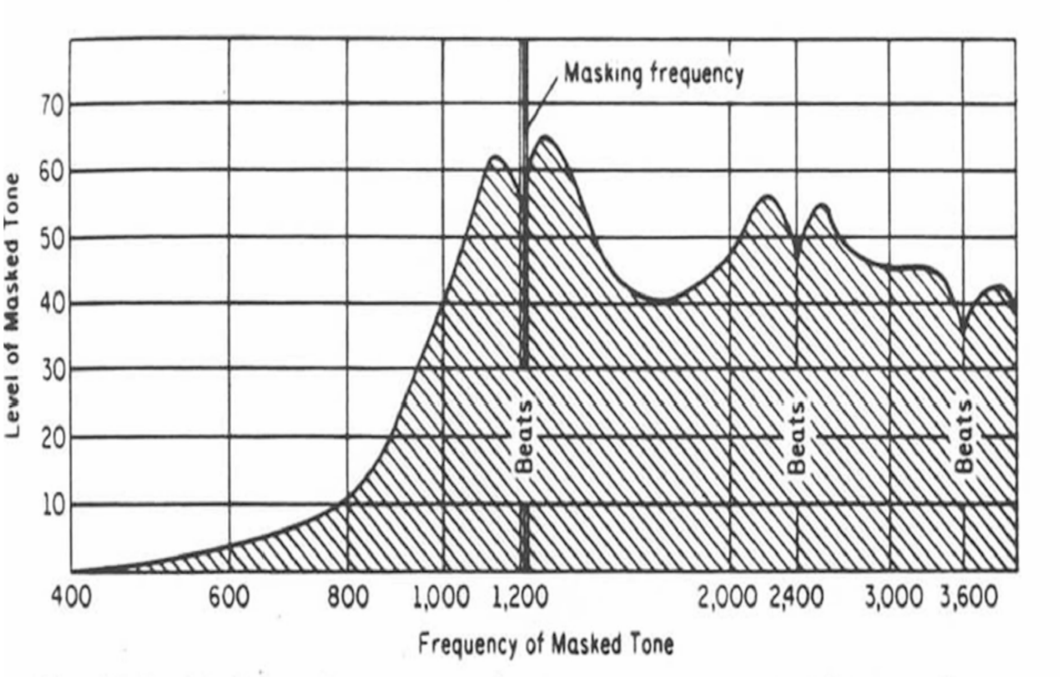

Figure 17. Masking of pure tones by a 1200 Hz tone at the 80 dB level.
The combination of frequency and the masked tone in the shaded area are inaudible.
(Adapted from Wagel & Lane, 1924).

In Figure 17, the masking effect of a 1200 Hz tone "masker" is shown by the shaded area; a listener will not hear any combination of frequency and intensity in the shaded area. For example, an 800 Hz tone requires only about 12 dB to be heard while a frequency of 1000 Hz requires a level of about 40 dB to be heard, and a frequency of 3000 Hz requires about 45 dB to be heard. Additionally, at 1200 Hz and its harmonics (2400 Hz and 3600 Hz), the aforementioned phenomenon of *beats* is observed. At these frequencies, the signal has a higher audibility (lower threshold) and reduced masking, simply due to the audible bits.

Masking by Narrow Bands of Noise

Other masking occurs when a tonal signal is masked by a narrow band of noise, as opposed to signal tone as describe before. Egan and Hake (1950) concluded that narrow bands of noise are more efficient maskers than are pure tones. The results of this study are illustrated in Figure 18 below.

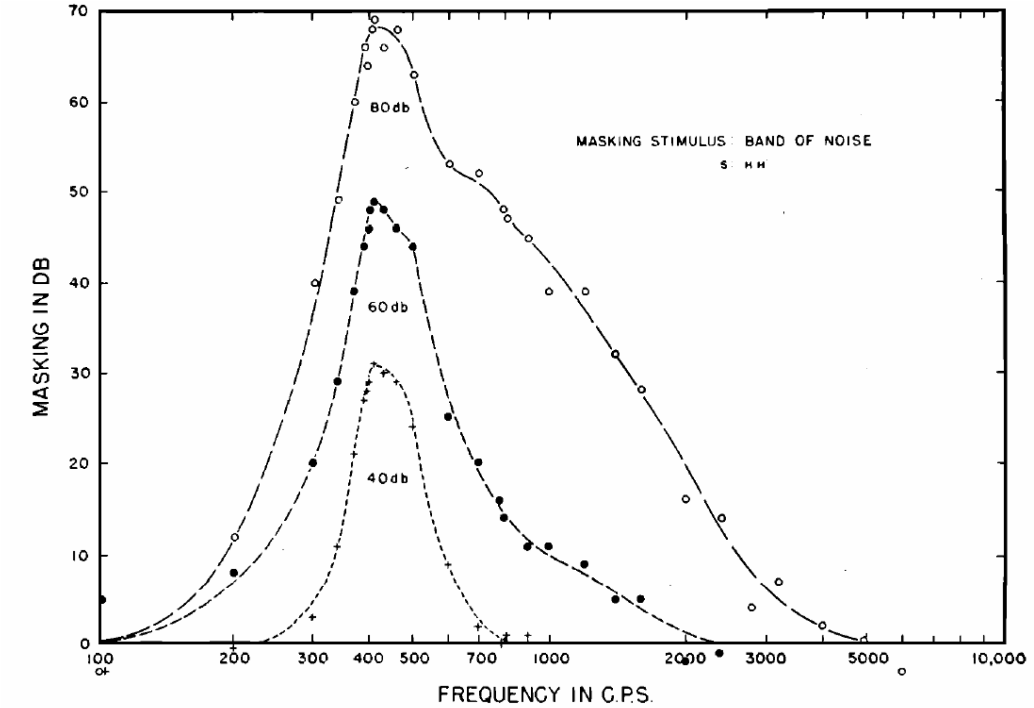

Figure 18. Masking (dB) vs. frequency of the masked tone (C.P.S/Hz) for the masking of pure tone with a narrow band noise (Adapted from Egan & Hake, 1950).

Figure 18 illustrates the masking of three different dB levels of a pure tone (with intensities of 40, 60 and 80 dB) by a 90 Hz wide band that is centered at 410 Hz. Upward spreading of masking is still apparent here as with the masking of one pure tone by another. It is also evident that the masking is not as complicated as with beats and the presence of harmonics as is the masking pattern with pure tones (Casali, 2005b).

Masking by Broadband Noise

Masking by broadband occurs when a tonal signal is masked by broadband (i.e., many different frequencies) of noise. Another classical study done by Hawkins and Stevens in 1950 illustrated this phenomenon. In their experiment, masked thresholds for pure tones were determined at 16 frequencies (from 100-9000 Hz) and eight levels of masking (-10 to 90 dB) in ascending order. Some of the results from this experiment are shown in Figure 19.

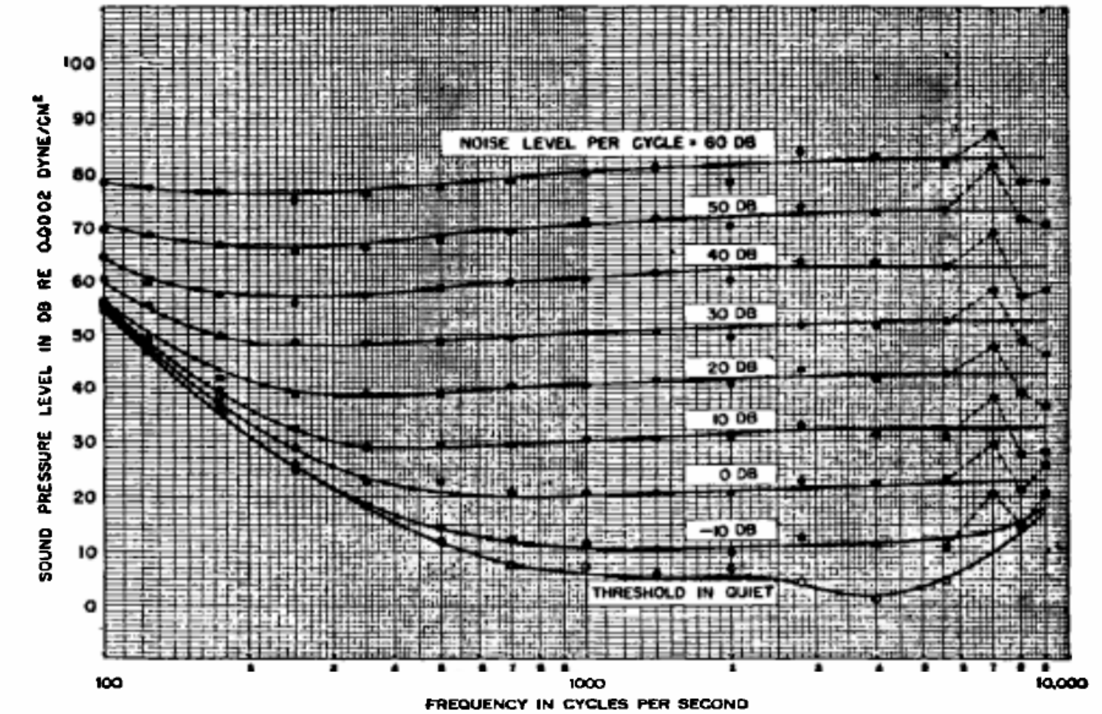

Figure 19. Masked threshold of a pure tone when masked by broadband noise (Adapted from Hawkins & Stevens, 1950).

As shown in Figure 19, the masked threshold contours at various noise levels tend to be parallel to one another. They are also separated by intervals of approximately 10 dB, which corresponds to the interval between the masking levels. This observation indicates proportionality between the masking produced by broadband and by level of noise. The frequencies above 6000 Hz become erratic due to the experimental apparatus used, according to the researchers (Hawkins and Stevens, 1950). Since the data shown are in “noise level per cycle in dB,” the broadband noise level would be 40 dB higher (i.e., a 1000 Hz noise bandwidth would have more intensity) than identified on the graph. So, for example, a 70 dB tone is just barely audible in white noise of (50+40) = 90 dB.

Since white noise contains all pure tones, all signal frequencies are masked with considerable efficiency. This is the main reason why white noise is often used in open office plans to reduce distraction (Casali, 2005b).

Predictive Models for Masked Threshold

There are a number of models that have been developed over the years to calculate or predict the masked threshold values of signals. Below is a brief explanation of three models that are used prominently in the literature.

Detectsound™ Laroche, Quoc, Hetu and McDuff (1991) developed a computerized model called 'Detectsound™' which can predict the capability of workers to detect auditory warning signals in noise. The main principle behind this approach is a *modeling excitation pattern* that would transpire if both noise and signal are presented. The stages of this model are shown in Figure 20. The initial stage of Detectsound™ takes into account how the signal would be affected by two attributes: gender and age. Attenuation by hearing protection is also taken into account. The second stage considers the transmission factor, which accounts for the way sound is transmitted from the outer to the inner ear, which varies non-linearly as a function of frequency. The third stage calculates the excitation levels produced at the ear, and provides the noise that is currently evaluated. In the fourth stage, the loudness of the sound involved is calculated, while the final stage involves calculation of total loudness and the superposition of the loudness and sounds. The excitation pattern that the ear produces is viewed as a visual pattern, and these can be superimposed. In a case where one pattern completely covers the other, then the covered sound is completely inaudible; thus, it is masked (Edwothy and Hellier, 2000). This model does not account for other forms of hearing loss such as NIHL, or *nosoacusis*, which is hearing loss caused by medical abnormalities (Ward, 1977). Example of nosoacusis can be anything from impacted earwax, which amendable to treatment, to severe deafness caused by Rubella during gestation (Suter, 1991)

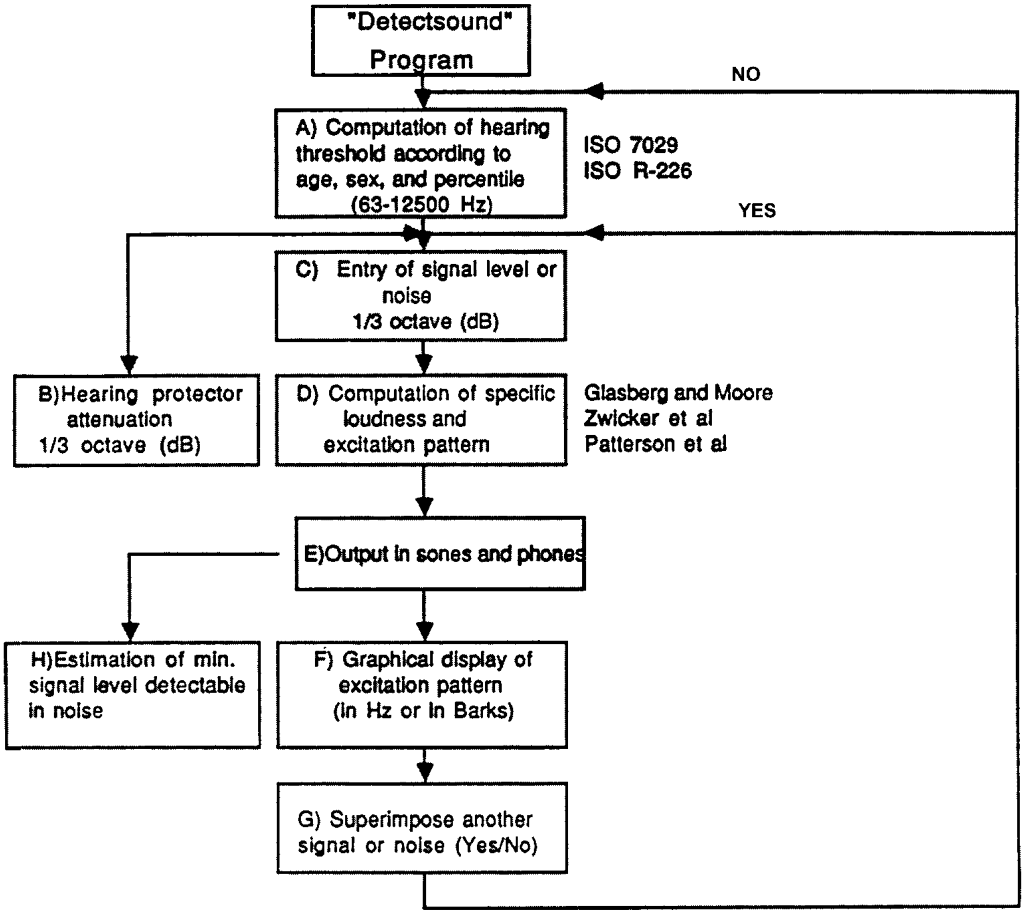

Figure 20. Flow chart for the stages of the Detectsound model (Adapted from Laroche et al., 1991).

Critical band theory. Another method used to calculate the masked threshold of a signal is based on critical band theory, which assumes that the masking noise is sufficiently flat. The masked threshold (L_{mt}) is computed using the following equation:

$$L_{mt} = L_{ps} + 10 \log (BW)$$

Where:

L_{ps} = the spectrum level (dB) of the masking noise around the area of the signal component being considered,

BW = Bandwidth; the width (Hz) auditory filter centered on the signal component to be calculated.

The spectrum level of the noise in the 1/3 octave band containing the signal is different from the band level measured using the octave band or the 1/3 octave band. By assuming that the noise is flat within the bandwidth of a 1/3 octave band filter, then the following equation can be applied:

$$L_{ps} = 10 \log \left(\frac{10^{L_{pb}/10}}{BW_{1/3}} \right)$$

Where:

L_{ps} = the spectral level of the noise (dB) within the 1/3 octave band

$BW_{1/3}$ = the bandwidth (Hz) of 1/3 octave band calculated multiplying the center frequency (fc) of the band by 0232

L_{pb} = the sound pressure level (dB) measured in the 1/3 octave band being analyzed

The bandwidth of the auditory filter can be calculated by the frequency of the masked signal by 0.15. The same procedures can also be used for calculations of octave band data by using bandwidth of octave band filter ($BW_{1/1}$= 0.707fc) instead of the $BW_{1/3}$.

This procedure is adopted from Robinson and Casali (2000). Standard: Ergonomics—danger signals for public and work areas—auditory danger

ISO 7731 Standard: Ergonomics-Danger signals for public and work areas- Auditory danger signals, ISO 7731:2003(E). The last method is the ISO 7731(E) standard. This method is widely used to determine the audibility of non-speech auditory displays, alarms and/or warning signals in noise. This procedure takes upward spread of masking into account since it compares the level of band in question to the level in the *preceding* band. The procedure for calculating the masked threshold of a signal in noise, for either an octave band or a1/3 octave band, is illustrated below.

Step 1: In the lowest octave band or the 1/3 octave band, i=1

$$L_{Ti} = L_{Ni}$$

Where: L_{Ni} is the noise level measured in 1/3 or full octave band.

Step 2: For each subsequent octave band or 1/3 octave band, i, the masked threshold (L_{Ti}) is the greatest value of the either the noise level in that band or the masked threshold value in the next band.

$$L_{Ti} = \text{max.}\ (L_{Ni}, L_{T\,(i-1)} - C)$$

Where C = 7.5 dB for octave band data or 2.5 dB for 1/3 octave band data.
Repeat step i for i=2… up to the highest octave band or 1/3 octave band.

The ISO 7731 method is also based on critical band theory. The masked threshold values under this standard solely depend upon the noise level. Once the masked thresholds are determined, the signal's spectrum can be compared to these masked thresholds to determine: a) if signals presented at known levels are audible in these noise conditions, and b) the levels to which these signals must be presented to be audible in these conditions. If at least one of the 1/3 octave band or full octave band exceeds the calculated masked threshold levels for a particular noise condition, then the signal should be audible—even if one is not paying attention. To ensure audibility under unfavorable conditions (such as periods of inattention or high workload) the standard recommends that the signal level exceed the masked threshold level by 13 dB on the 1/3 octave and 10 dB for octave band (ISO 7731:2003(E)).

The standard takes account of moderate degrees of hearing impairment by: (a) incorporating a suitable correction for masking, (b) specifying a minimal level of A-weighted signal, and (c) avoiding signals at high frequencies.

This same method is also applied when HPDs are worn by reducing, in every frequency band, the levels of noise and signal by the relevant mean sound attenuation of the HPD. Calculating an occluded masked threshold for a particular signal requires the following:

1. Subtracting the attenuation of the HPD from the noise spectrum to obtain the noise spectrum that is effective when the HPD is worn.
2. Calculation of masked threshold for each signal component using the procedure outlined in the preceding section, which resulted in the signal component levels being *just audible* when wearing an HPD.
3. Adding the attenuation of the HPD to the signal component thresholds to provide an estimate of the environmental (i.e., exterior to the HPD) signal-component levels that would be required to produce under-HPD threshold levels calculated in Step 2. This procedure requires a reliable estimate of the HPD's attenuation. The manufacturer's attenuation data that comes with the HPD are often unreliable for this purpose because they overestimate the real-world performance of the HPD (ISO 7731:2003(E)).

The standard also states that the danger signal should include frequency components in the 500 to 2500 Hz frequency range. However, the two most dominant components should be between 500 Hz to 1500 Hz. In the case in which a person has hearing loss or is wearing a HPD, sufficient signal energy should be present in the frequency range below 1500 Hz.

In a noisy environment such as the construction industry, vehicle backup alarms are routinely used, which are necessary for warning workers in the vicinity of a reversing vehicle that the vehicle is backing up. The section that follows will discuss the evolution of signal detection from past research papers.

SIGNAL DETECTION

Signal to noise ratio (S/N)

The methods that were discussed in the previous section are intended to determine the masked threshold (i.e., the elevated minimum levels that a sound can be heard), and *not* the level at which the signal can be reliably heard 100% of the time. To ensure audibility and overcome any decrement due to inattention, the signal level must be increased above the threshold level (Robinson and Casali, 2000), which is known as the signal to noise ratio (S/N). In its simplest terms, S/N is the signed (+/-) difference between a broadband signal measurement and a broadband noise measurement, and is outlined with the equation that follows (Casali, 2005b):

$$\text{S/N Ratio} = \text{Signal in dB} - \text{Noise in dB}$$

The ISO 7731 (2003E) standard requires that for any measurement of A-weighted sound pressure level, the S/N be greater than +15 dB, and also that the A-weighted sound pressure level be at least 65 dB.

Masked Threshold Research

The masking of essential signals by Masking noise is a source of concern in any environment that relies on the use of auditory signals. Studies have revealed that, in noisy environments, an unoccluded ear has difficulty in perceiving speech or other auditory cues (Suter, 1989; Casali et al., 2004). This difficulty arises mainly because of the distortion that results in the cochlea, as discussed earlier. The use of HPDs tends to reduce this distortion, making it easier for listeners to perceive speech and other essential cues.

One of the earliest recorded cases of HPDs *interfering* with hearing abilities was reported by Barr (1886). In this instance, boilermakers rejected using HPDs (earplugs) while working, mentioning that they interfered with their hearing. Barr, however, doubted the validity of such claims, and so he wore the plugs himself. He observed that, while using the plugs, he was able to perceive the voice of a speaker more easily, ultimately refuting the claims that hearing protection interfered with speech perception.

Wilkins (1983) performed a field study to assess the effects of wearing hearing protectors on the perception of warning signals in an industrial setting. A total of 30 subjects were used. These subjects were further subdivided into three categories, which were: 1) those with substantial hearing loss, 2) those with mild hearing loss, and 3) those with normal hearing. Two types of warning sounds, one on a horn on one of the fork lift trucks, and another as a 'clicking' sound from metal components spilling from their container, were used in the study. The Masking noise consisted of three sources: 1) the sound of an overhead crane, 2) the sound of a normally operating 40-ton press, and 3) the sound of 120-ton press with noisy gearing; these sounds and their intensities were typical in an industrial setting (85-95 dBA). Results showed that the perception of the intentional horn warning was unaffected by the hearing sensitivity of subjects while wearing hearing protectors. Subjects, however, showed a different response to the clicking sound, potentially due to its higher frequency content than its lower frequency content. Subjects classified as having a substantial hearing loss at high frequencies perceived fewer clicking sounds (18% fewer) than did those with normal hearing and mild hearing loss. The subjects also perceived fewer clicks (9% fewer) when wearing hearing protectors (Wilkins, 1984).

Abel and Kunov (1983) performed a study to investigate the effect of hearing protection on narrow band signal detection in an industrial setting. Participants were divided into two groups; those with normal hearing, and those who suffered from NIHL. The industrial noise was created from a cassette and was fixed at 84 dBA. The narrow band signals were created by a noise generator and were varied across blocks of 50 trials, ranging from 'near threshold' to 'clearly audible.' Normal participants showed improved hearing abilities (by an average of 3 dBA) while wearing protectors. On the other hand, the hearing-impaired listeners showed a substantial decrement in signal detection while wearing HPDs. The latter virtually became deaf at all conditions, i.e., for both signals, the occluded and unoccluded ear had a range of threshold that was well over 100 dBA for a noise intensity of 84 dBA.

Edwothy and Hellier (2000) gave a complete review of warnings in noisy environments. They mentioned the importance of auditory warnings in industries such as aviation, control rooms, and factory floors, where noise is a constant issue. A comparison of the most common modalities of presenting warnings (i.e., visual and auditory) was made. Research showed hearing as the primary warning sense, in that a sound that is loud enough will be heard, and there is nothing that one can do in terms of blocking out the sound. Contrary to that contention, for vision, one needs to be looking at the right place at the right time and can more easily ignore visual stimuli. However, many of the situations where auditory warnings are necessary were found to be masked by intense noise levels at times. Such situations might include a cockpit of a helicopter or a flight deck of an aircraft where the noise will vary as a function of speed, height, and current activity; all of these variables need to be taken into account. The Patterson model (1982) is used to illustrate this example (see Figure 21).

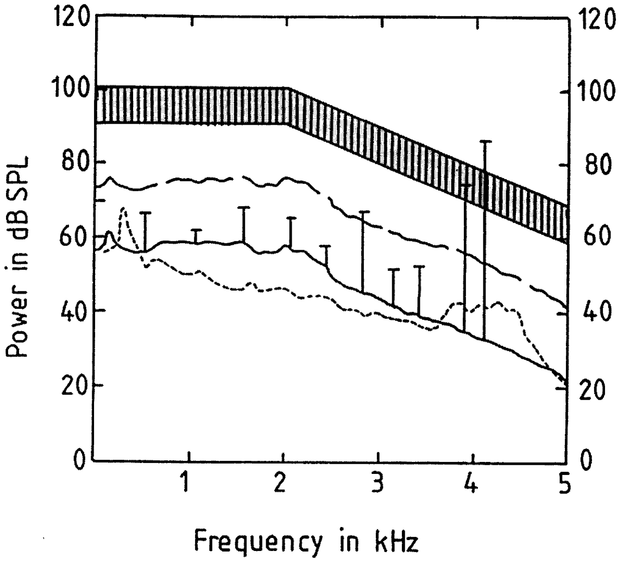

Figure 21. Noise spectrum, threshold, and appropriate band for auditory warning components and components of a single warning auditory warning for a BAC 1-11 aircraft (adopted from Edworthy & Hellier, 2000 as in Patterson, 1982).

Figure 21 shows the noise spectrum of an aircraft wing with threshold and auditory calculations. The lowest solid line shows the noise spectrum when the plane is flying normally, at reasonable speed. The dashed line shows spectrum for other rare conditions. The next solid line above the lowest solid line shows auditory threshold as predicted by the Patterson model when the plane is flying normally at reasonable speed. The solid shaded area is the appropriate band for auditory warning components. The lower of these lines is 15 dB, and at this level warning signals are quite audible and are hard to miss. The upper line is 25 dB above masked threshold, and at this level, nothing is really gained. There is much to be lost as the warning might become excessively loud and might be switched off by the user as a result, thus rendered useless. Ultimately, it is important that the signals used are not excessively noisy, but are instead loud enough to be heard (Edworthy & Hellier, 2000).

Signal Detection Under Augmented HPDs

A very few studies have examined the effectiveness of augmented HPDs on communication and detection abilities (e.g., Casali et al., 2004). In the Casali et al. 2004 research, the experimenters analyzed the effects of ANR and conventional HPDs on backup alarm detection. The types of HPDs used were a Bose ANR earmuff, an EAR (AEARO) Classic™ slow-recovery PVC foam earplug, and a Peltor H9A™ passive earmuff. A secondary objective was to investigate whether or not an unoccluded ear had lower masked threshold values for a backup alarm than did an occluded ear. A total of 10 participants with normal hearing were used for the experiment. Red and pink noise, each presented at 85 dBA and 100 dBA levels, were used as the Masking noise. Results revealed a significant difference (i.e., 2.6 to 4.3 dBA) among HPDs at 100 dBA; this was somewhat surprising in that the earplug produced lower masked threshold values than did both the ANR and the conventional earmuff. There were no significant differences at 85 dBA. The researchers concluded that the lack of a HPD effect at 85 dBA may indicate that even though the two noise spectra contained significant lower frequency energy, the sound pressure levels at these frequencies were not high enough for upward spread of masking of the dominant signal frequencies to occur. Consequently, there was no relevance in low-frequency attenuation among the HPDs. However, this was not the case at the higher noise level, as stated as follows: "At the 100 dBA level, however, the upward spread of masking from low-frequency noise probably did affect masked threshold, and the better low frequency attenuation afforded by the form earplug, and to a smaller extent, by the ANR earmuff, provided an advantage over the passive earmuff, which had more limited attenuation below 500 Hz."(Casali et al., 2004, p. 7) There was also a significant difference in red noise (i.e., 2.3 to 3.1 dBA), with the passive earmuff resulting in higher masked thresholds than did the earplug or the

ANR earmuff. This was probably due to the higher concentration of low-frequency concentration in red noise, and the stronger low-frequency attenuation of the ANR muff. Further, the foam earplug was not affected by masking as much in this noise spectrum, resulting in lower threshold than the ANR and the conventional earmuff. Another finding was that in the 85 dBA noise level, all of the HPDs under study did not hinder, but in-fact *aided,* one's ability to detect a backup alarm; this same result was also reported by Suter (1989), in her review publication.

The only study to date that has tested the masked threshold performance of sound transmission devices with their passive counterpart was conducted by Casali and Wright (1995). There were a total of twelve subjects, all with pure tone Hearing Abilitys (HTL) of 25 dB or less from 125 to 8000 Hz. Pink noise at three different noise levels (75, 85 and 95 dBA) was presented as stimuli in the study. The objective of the study was to compare detection performance achieved under two contemporary (as of 1995) sound transmission devices, an electronic Peltor T7-SR earmuff and a passive, orifice type E-A-R Ultra 9000 earmuff, against the detection achieved under the conventional counterparts of these muffs, a Peltor H7A™ and an E-A-R 2000. The subjects performed a method of limits psychophysical protocol, in which the alarm was adjusted in dB level through an audiometer according to a Hughson-Westlake audiometric procedure. The dependent measure was masked threshold in *dB linear* for the backup alarm signal (Casali and Wright, 1995).

Subjects' masked threshold in dB was computed as an arithmetic mean of 10 trials for each muff/noise combination. The data were subjected to an analysis of variance (ANOVA) with treatment and order as factors. Neither the order nor the treatment was significant ($p > 0.05$); therefore, it was concluded that the subjects` mean thresholds were similar over different orders of presentation of the experimental condition over the muff/noise condition. Other results of the study showed that at the noise levels presented, assistive listening devices did not show any advantages over conventional HPDs. The researchers suggested that the dependent measure may have been of insufficient fidelity to result in significant differences (i.e., subjects' threshold values were at 5 dB increments, instead of a more precise increment).

JUSTIFICATION FOR THE RESEARCH

In an environment such as construction, with its hazardous and intense noise levels, the role of warning signals is of high importance. One of the most common types of signals in the construction environment is the backup alarm, which functions whenever vehicular equipment (e.g., trucks, bulldozers, backhoes) is reversing. However, the existing hearing loss among the population of construction workers (in some cases due to both worksite noise levels and other non-work, outside activities), in combination with the preponderance of noise at construction sites, can contribute to the occurrence of accidents that can result in personal injury and/or death. These accidents may have been due to the fact that an important signal was not heard. It is likely that at least some of these deaths could have been avoided if the vehicles and their operations had been clearly audible to the workers. Based on the available evidence, it appears that there is a safety-related need to examine the ability to hear auditory signals (e.g., backup alarms, horns) within the construction industry.

Sound transmission devices appear to have promise as interventions on construction sites to not only protect worker hearing, but to also foster signal detection. While the aforementioned research into various HPDs (including sound transmission devices) has been: 1) very limited, and 2) mixed as to results, newer HPD designs have surfaced in the past several years, suggesting that the potential for these systems to improve signal detection exists (Casali, 2005a). Further, in at least one study (Casali & Wright, 1995) in which there were no significant differences between conventional and sound transmission devices with respect to masked threshold, there may have been too insufficient a resolution in the Hughson-Westlake method instituted (i.e., 5 dB steps) to be sensitive to actual differences. Perhaps in a similar, but more realistic experiment in which the resolution was more precise and measurable, significant differences in masked threshold detection between more modern devices may indeed result.

The purpose of this study was, therefore, to evaluate the effectiveness of using current sound transmission devices to augment signal detection (e.g., backup alarms of other equipment), which are routine and necessary considerations at construction sites, and comparing their performance with existing, conventional HPDs of similar design and passive attenuation (OSHA, 2000).

RESEARCH OBJECTIVE

The primary objective of this research study was to investigate if there was any advantage in using current sound transmission earmuffs over conventional (passive) HPDs, for both normal and non-normal hearers, in the detection of a backup alarm within the noise produced by construction equipment, and within pink noise at various levels.

Hypotheses

H_1: The sound transmission devices would result in a lower masked threshold value, for both normal and non-normal listeners, when compared to passive HPDs of similar design for noise levels at 75 dBA.

H_2: At noise levels above 85 dBA, *both* types of HPDs (i.e., sound transmission and passive) are expected to result in the same masked threshold values for both normal and non-normal listeners. This is because at noise levels above 82 dBA the electronics of the sound transmission devices are expected to shut off, allowing the device to work as passive devices.

METHODOLOGY

Experimental Design

The experiment was a 2X4X4X2 mixed-factor design with a *Masking noise Type* variable (2 levels), a *hearing protection device type* variable (4 levels), a *Masking noise level* variable (4 levels), and a *hearing threshold* variable (2 levels) (figure 22). Each independent variable is discussed briefly here, and is discussed in more detail below. The structural model for this design is diagrammed below:

$$\begin{aligned} Y_{ijklm} &= \mu + \alpha_i + \beta_j + \delta_k + \tau_l + \gamma_{m(l)} + \alpha\beta_{ij} + \alpha\delta_{ik} + \alpha\tau_{il} + \\ &\beta\delta_{jk} + \beta\tau_{jl} + \delta\tau_{kl} + \alpha\beta\delta_{ijk} + \alpha\beta\tau_{ijl} + \beta\delta\tau_{jkl} + \alpha\gamma_{im(l)} + \beta\gamma_{jm(l)} \\ &+ \delta\gamma_{km(l)} + \alpha\beta\gamma_{ijm(l)} + \alpha\delta\gamma_{ikm(l)} + \beta\delta\gamma_{jkm(l)} + \alpha\beta\delta\gamma_{ijkm(l)} + \\ &\varepsilon_{n(ijlkm)} \end{aligned}$$

Where:

Y = observations

μ = population mean

α = spectrum type (i=2, pink and manipulated pink noise to mimic road milling machine)

β = HPD type (j=4, HPD 1-4)

HPD 1 = Bilsom® Impact™
HPD 2 = Bilsom® Clarity™ C2
HPD 3 = Peltor TacticalPro™
HPD 4 = Peltor H7™

δ = Noise level (k=4, 75, 85, 95 & 105 dBA)

τ = Hearing abilities (l=2, normal and non-normal)

γ = Subjects (11)

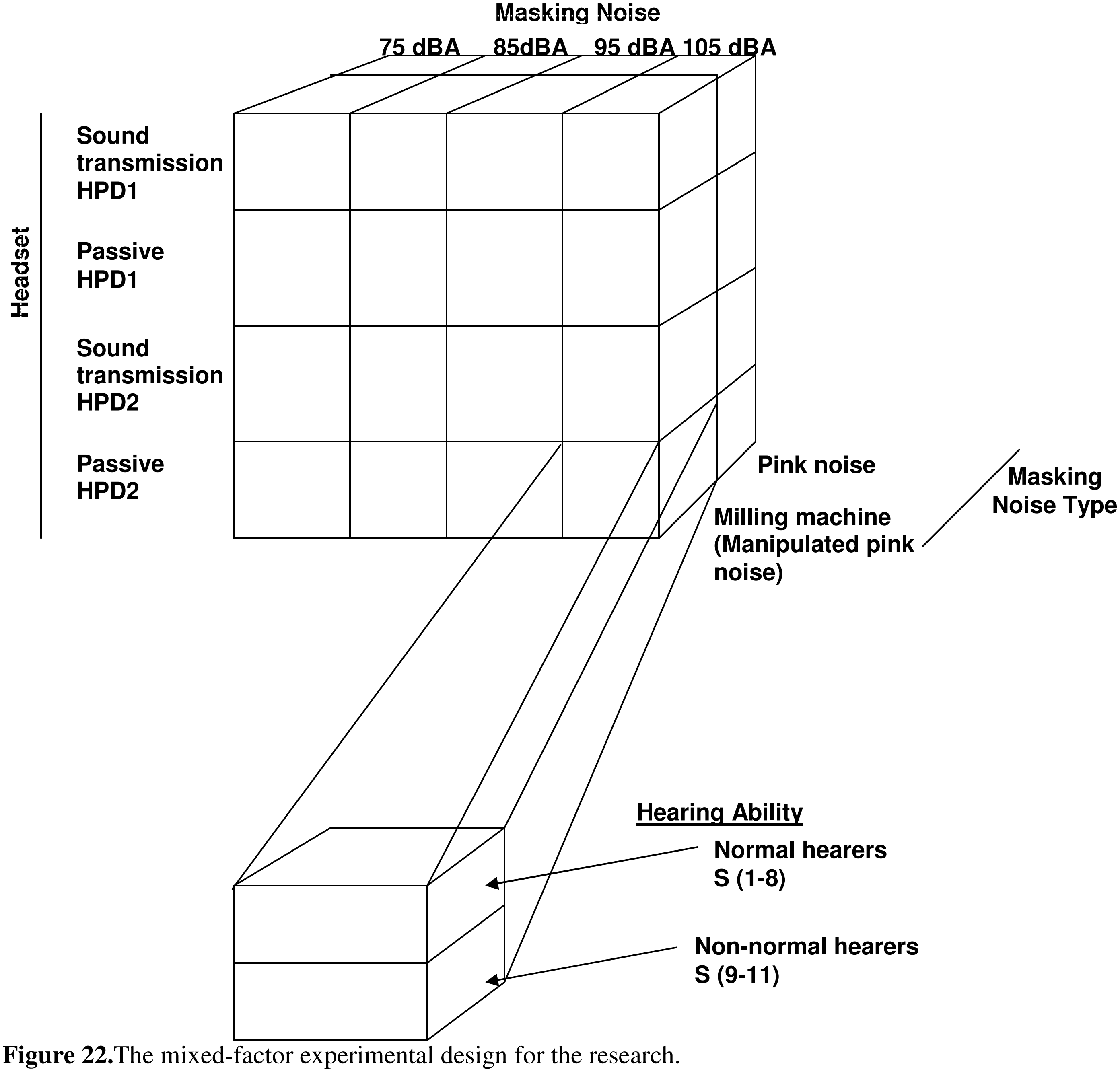

Figure 22. The mixed-factor experimental design for the research.

Participants

Initially and based on a statistical power analysis as discussed below a total of 16 participants were to be used, eight of which were normal hearers and the other eight which would have been individuals with elevated pure-tone thresholds (i.e., hereafter termed "non-normal hearers"). However, due to the unavailability of individuals who met the non-normal hearing criteria, only three participants who met the criteria could be recruited. It should be noted that exhaustive efforts were undertaken to identify and recruit non-normal hearers, including advertisement via listserv and postings, contacting local audiologists and reviews of audiograms from over 700 patients of a local Hearing and Speech Pathology program at Radford University per Davis and Silverman (1978).

Power Analysis. Power analysis calculations were conducted to determine the number of participants that results in reasonable statistical power for this experimental design. In human factors research, a statistical power of at least 0.8 is normally required. The equation for this analysis is shown below**:**

$$\delta = \frac{A - B}{\sigma \sqrt{\frac{2}{n}}}$$

Where:

A = the mean dB value for normal hearers (25 dB)
B = the mean dB value for non normal hearers (50 dB)
σ = the standard deviation (15.75 dB)
α = alpha-level of 0.05

This model makes an assumption in the standard deviation value (σ): that there is no one specific standard deviation value that has been recorded for either normal or non-normal hearing individuals. The standard deviation value used in this experiment, therefore, was based on recent research by Hong (2005) on the hearing loss as measured among operating engineers in the construction industry. In the Hong research, audiograms for 623 participants were gathered, which provided the standard deviation of the worst ear (worst case scenario) at 2000 Hz (15.7 dB); this value was used in the power analysis to determine the appropriate sample size for this study (Table 3).

Table 3. Results of the power analysis for the proposed research.

N	**n**	**df_{N-2}**	**δ**	**Power**
8	4	6	2.244783	0.470
10	5	8	2.509744	0.665
12	6	10	2.749287	0.688
14	7	12	2.969569	0.778
16	8	14	3.174603	0.827
18	9	16	3.367175	

The results of the power analysis indicate that 16 (Power> 0.8) was a sufficient number of participants to be used; however, as mentioned earlier, due to the difficulty in recruiting individuals meeting the non-hearing criteria, only 3 non-hearing individuals participated in the experiment.

Independent Variables

In this controlled human factors laboratory experiment, the independent variables that were manipulated included: Masking noise (i.e., type, spectra), Masking noise level (i.e., intensity in dBA), hearing protector type (make/model), and the hearing threshold of the listeners with normal hearing and those with hearing loss_(i.e., 'normal hearers,' and 'non-normal hearers,' respectively). All independent variables, with the exception of the hearing threshold variable, were presented as within-subjects in that each participant attended all experimental sessions and experienced all levels of each independent variable. The hearing threshold variable was presented as the sole between-subjects variable.

Participants and Hearing threshold.

A total of 11 subjects, ranging in age from 19 to 65 years of age, participated in the experiment as paid volunteers. Screening criteria were based on the participants' pure tone hearing thresholds, and were stratified as follows:

1. Individuals with normal hearing.
2. Individuals with elevated hearing levels (non-normal hearing).

The participants with *normal hearing* had pure tone Hearing Abilitys in both ears at the 1/3-octave band center frequencies from 125 Hz-8 KHz that were ≤ 25 dBHL (Ward, Royster, and Royster, 2000). Participants with *non-normal hearing* had an average hearing (threshold) level in the better ear that was above 40 dBHL in the 1000, 2000 and 3000 Hz frequencies (Davis and Silverman, 1978).

Masking Noise Type. Two types of Masking noise were used for this study, namely pink noise (see Figure 23a) and pink noise that had been manipulated to match the spectrum of a 1994 CMI PR-500B road-milling machine (J.A Lancaster, personal communication, August 2005. The spectrum is illustrated in Figure 23b.

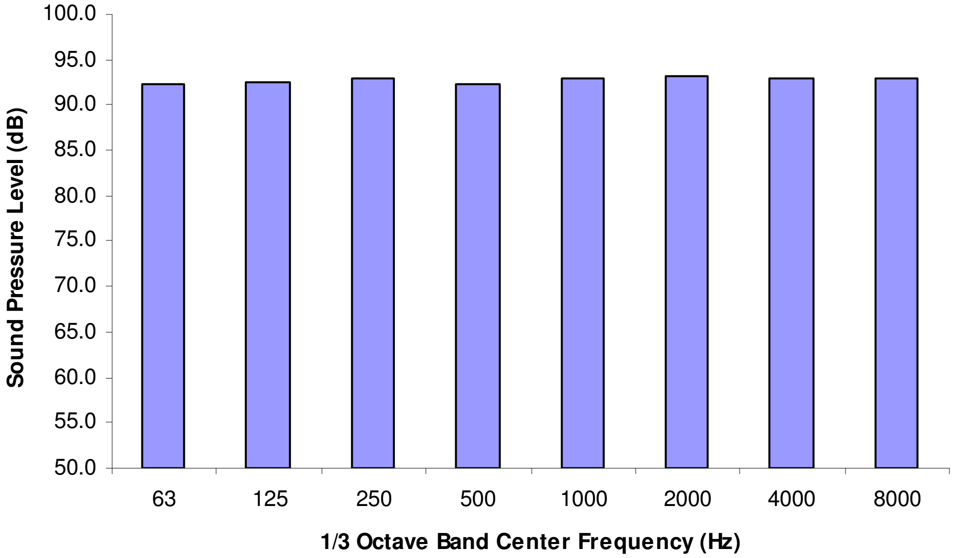

Figure 23a. Pink noise spectrum.

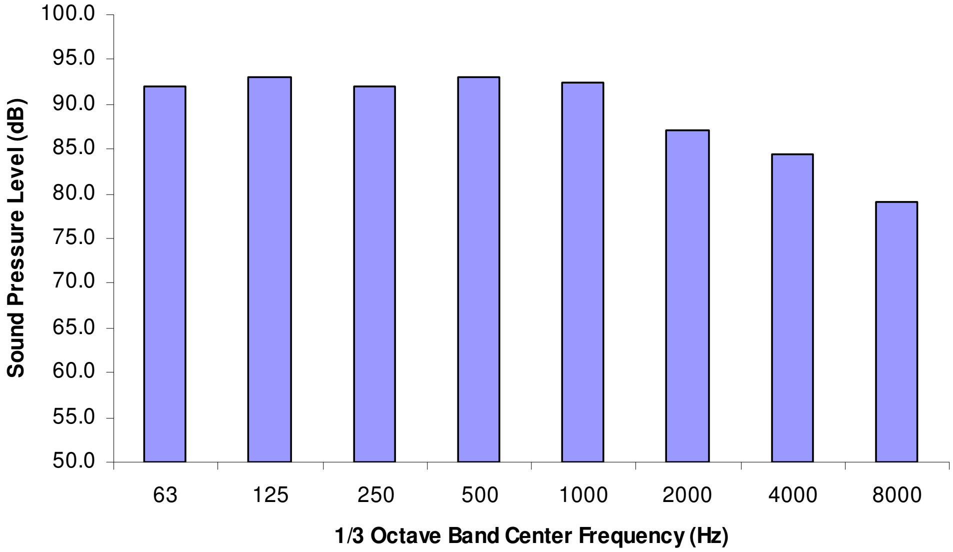

Figure 23b. Spectrum of a 1994 CMI PR-500B road-milling machine

A characteristic of a pink noise spectrum as shown in Figure 23a is that it is flat-by-octaves across all frequencies (63-8000 Hz). Pink noise is a common type of noise spectrum used in masked threshold research because it provides the maximum opportunity for broadband masking (e.g., intensity changes in S/N ratio are easily noted at each frequency). Examples of masked threshold research using pink noise include research by: Casali et al., 2004; Casali and Robinson, 1995; and Casali & Wright, 1995.

The road milling machine was selected as an independent variable for two reasons: 1) the milling machine produces intense noise levels that are typical of construction equipment (TWA 94.7 dBA and, Leq of 95.7 dBA) (J.A. Lancaster, personal communication, August 2005), and 2) the milling machine presents the need for the hearing of its backup alarm by ground personnel in the vicinity of the machine (e.g., rakers, screedmen, foremen).

Masking noise level. Four noise levels were manipulated in this experiment. These levels (in ascending order) were 75, 85, 95 and 105 dBA. The 75 dBA represented a low noise level where HPDs are not required (per OSHA) to be worn by a worker—it is at this level that differences in HPD type were expected to occur due to the amplification qualities of the sound transmission devices when compared to their passive counterparts. The 85 dBA level was selected because it represented the OSHA (1983) "action" level: action must be taken to protect workers at or above an 8-hour TWA of 85 dBA. At this level, a full hearing conservation program is required and HPDs must be supplied to all workers (as discussed). The 95 and 105 dBA levels were selected because they represent the high noise levels endemic at construction worksites (J.A. Lancaster, personal communication, August 2005).

*Hearing Protection Device Type.*Four HPDs in the form of circumaural earmuffs were used in this experiment. Two of these earmuffs, the Bilsom® Impact™ and the Peltor

TacticalPro™, were sound transmission muffs. The other two earmuffs, the Bilsom® Clarity™ C2 and the Peltor H7™, were the passive counterparts to the two sound transmission devices in terms of their design, construction, and materials, as well as their construct NRRs. The NRR for the Bilsom® Clarity™ C2 and the Bilsom® Impact™ is 23. The NRR for the Peltor TacticalPro™ and the Peltor H7™ is 26. The NRR for the two sound transmission devices is obtained while the electronics are off. Stratifying the HPD variable in this manner allowed direct comparisons to be made between the sound transmission and conventional, passive products of similar design (with respect to their earcup volume, cushion design, and EPA-labeled noise reduction rating [NRR]). The brand names/models or any identifying marks of each device were covered with tape to avoid bias. To determine which devices may be suitable as interventions for construction workers to help improve speech and signal detection, a pilot study was conducted on several amplitude-sensitive devices within various levels of Masking noise (J.G. Casali and J.A. Lancaster, personal communications, May 2006), and this is discussed below.

Pilot Study of Prospective Interventions. Utilizing an acoustical test fixture (ATF, ANSI S12.42-1995) and microphone spectrum analyzer measurements, five candidate sound transmission devices were tested in ambient pink noise levels of 75 dBA, 80 dBA, 85 dBA, and 90 dBA to determine their under-the-headset levels (i.e., sound-transmission values) at each tested frequency between 25 Hz—20,000 Hz. The devices were: the Bilsom Impact™, Bilsom Electro™, Peltor Push-to-listen™, Peltor TacticalPro™, and the Deben Slim Electronic™. As each of the devices (with the exception of the Peltor 'Push-to-listen' device) maintained a *gain control* feature, the devices were tested within each level of pink noise at the following settings: 'off' (i.e., passive), 'half-gain,' and 'full-gain.' The Peltor 'Push-to-listen' device only had 'on or off' functionality, so it was tested for its under-the-headset levels at both of these functional positions. In addition to the ATF, measurement apparatus included a Larson-Davis 3200 Series real-time spectrum analyzer, a Larson-Davis 1/2" microphone and preamplifier (models #2559 and 900B, respectively), a Larson-Davis 1" microphone and preamplifier (models #2575, and 910B, respectively) and a Quest QC-20 calibrator. Sound generation and production apparatus included an Atlas Soundelier GPN-1200A pink/white noise generator, an Audiocontrol model C-131 1/3-octave band equalizer, a Realistic model 31-2020A 1/3-octave band equalizer, two Sony STR-DE135 amplifiers, and three Infinity RS 6-B loudspeakers. Two of the three Infinity speakers were connected to one of the Sony amplifiers, with the third speaker connected to the other Sony amplifier and the sound field was diffused inside a reverberant chamber. To ensure appropriate gain settings for the headsets, the setting of 'off,' 'half-gain,' and 'full-gain' was pre-set and marked with labels at each of these positions on the headsets.

The procedure for testing the headsets was as follows:

1) The Larson-Davis model #2559 1/2 microphone was calibrated to 94 dBA at 1000 Hz.
2) The microphone was then placed in the central position in the reverberant chamber (indicated by a plumb-bob).
3) Using the Larson-Davis Spectrum Analyzer and 1/2" microphone, the Infinity speakers were equalized. To do so, the Atlas noise generator was set to produce a level pink noise spectrum by first outputting the pink noise into the Sony amplifier controlling two of the Infinity speakers, wherein the pink noise spectrum was set as 'flat' using the Audiocontrol equalizer and, once satisfactory, the third speaker's pink noise output was also set as 'flat' using the Realistic equalizer.
4) A 15-second L_{eq} measure was taken and used to manipulate the pink noise intensity to the desired level of pink noise (as noted earlier).
5) The ATF with 1" microphone was positioned in the center of the reverberant chamber, and the desired level of pink noise was verified and recorded.
6) A headset was placed on the ATF, whose setting was either 'off,' 'half-gain,' or 'full-gain.'
7) A 15-second L_{eq} measure was taken in the right earmuff of the HPD.
8) Steps 4-7 were repeated at each dB setting, and in each level of pink noise to result in under-the-headset intensity measures for each headset, for each gain setting, and within each level of pink noise.

The results for each headset were evaluated with respect to their sound-transmission capabilities, particularly within the frequencies of 1000-4000 Hz, which would provide some indication of a particular headset's effectiveness at amplifying the most important (for intelligibility) human speech and backup alarm signal frequencies. Two of the devices i.e., the Bilsom Impact™ Peltor TacticalPro™ were selected as candidate devices for this experiment because of their better design, construction, and sound amplification abilities which made the two more applicable in the construction environment when compared to the Bilsom Electro™ and Peltor Push-to-listen™. Selected results are presented in this section under the appropriate sound transmission device subheading.

- <u>Bilsom® Impact™.</u> The Bilsom® Impact™ has electronic noise filtering that is designed to protect the ears from harmful Masking noises and amplifies sounds one wants to hear, such as verbal communication and warning signals (see Figure 24), and a NRR of 23 (Bilsom® Impact™ website). When the electronics are off, the sound transmission device attenuates the noise as a passive HPD. When the electronics are turned on, the amplifiers boost the intensity of desirable external signals (such as a backup alarm) to a level at which should be more easily detected. This effect is illustrated in Figures 25a, 25b and 25c at the respective noise levels, which were gathered during the aforementioned Casali and Lancaster research (2006) utilizing an acoustical test fixture. At the 75 dBA external noise level, the sound heard around the peak back-up alarm frequency (1250 Hz) is amplified to 68 dBA when the HPD is at full gain, which is an amplification of 12 dBA when compared to when the electronics are turned off (see Figure 25a). As the pink noise is increased to 85 dBA, the under-earcup maximum was measured to be 72 dBA at the reverse alarm frequency at the full gain setting (see Figure 25b). At the 90 dBA pink noise level, the under the ear-cup maximum was measured to be 73 dBA for the reverse alarm frequency at the full gain setting. Similarly, the speech frequencies (1-4 KHz) were also amplified. At the 75 dBA pink noise level at full gain setting, the dB linear sound level was 69 dBA. At the 85 dBA external noise level, the dB linear sound level was amplified to a higher level of 76 dBA. At the 90 dBA external noise level, the dB linear sound level increased to a level of 77 dBA. It is also important to note that in the 90 dBA noise, the device should not amplify sound more than it does in the 75 dBA and 85 dBA noise, but there either was some amplification and/or the 90 dBA noise simply overcame the muff's passive attenuation. According to the manufacturers, the actual limiting level of amplification for this HPD is a 'safe' 82 dBA. This HPD may be helpful for hearing-impaired workers due to its amplification abilities (www.labsafety.com).

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Figure 24. The Bilsom® Impact™ sound transmission earmuff, NRR = 23.

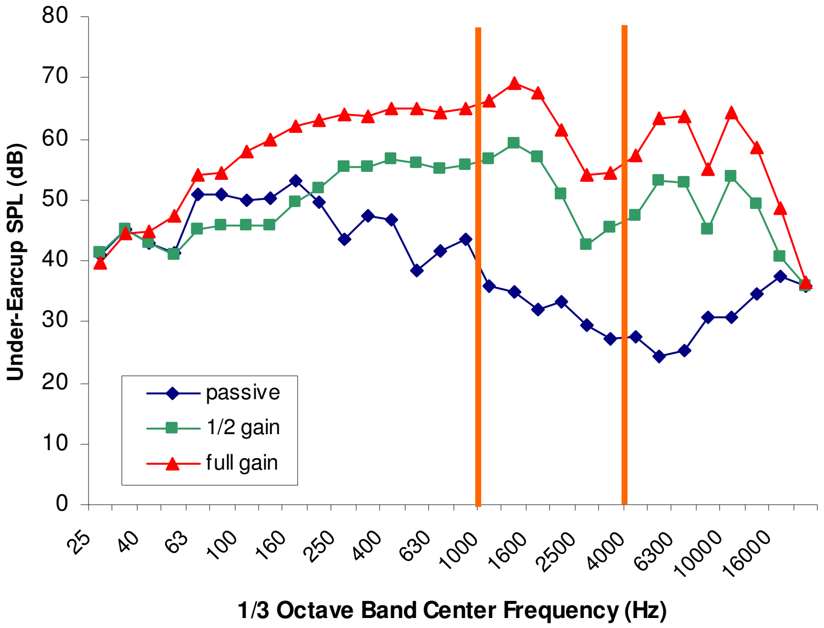

Figure 25a. Under-the-earcup spectra and noise levels for the Bilsom® Impact™ amplitude-sensitive earmuff within 75 dBA pink noise using an ATF. The vertical lines represent the frequency range for most warning signals, including backup alarms.

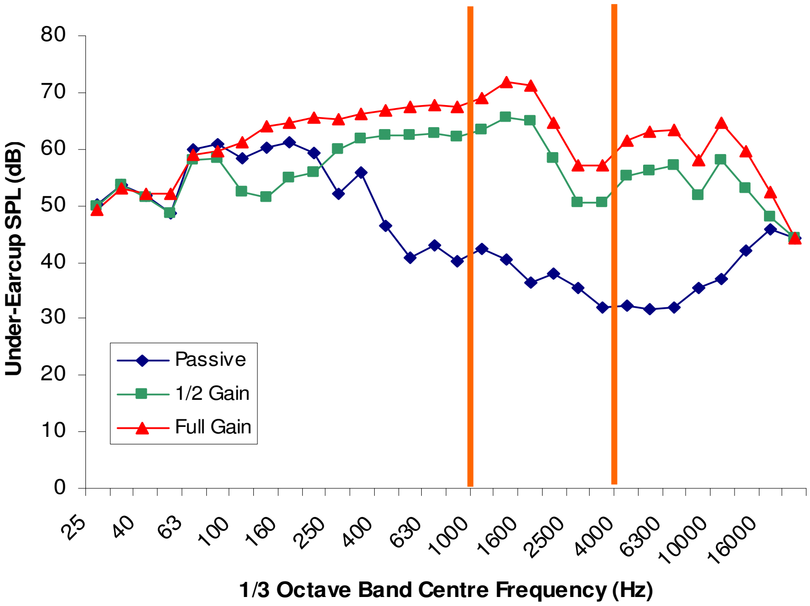

Figure 25b. Under-the-earcup spectra and noise levels for the Bilsom® Impact™ amplitude-sensitive earmuff within 85 dBA pink noise using an ATF. The vertical lines represent the frequency range for most warning signals, including backup alarms.

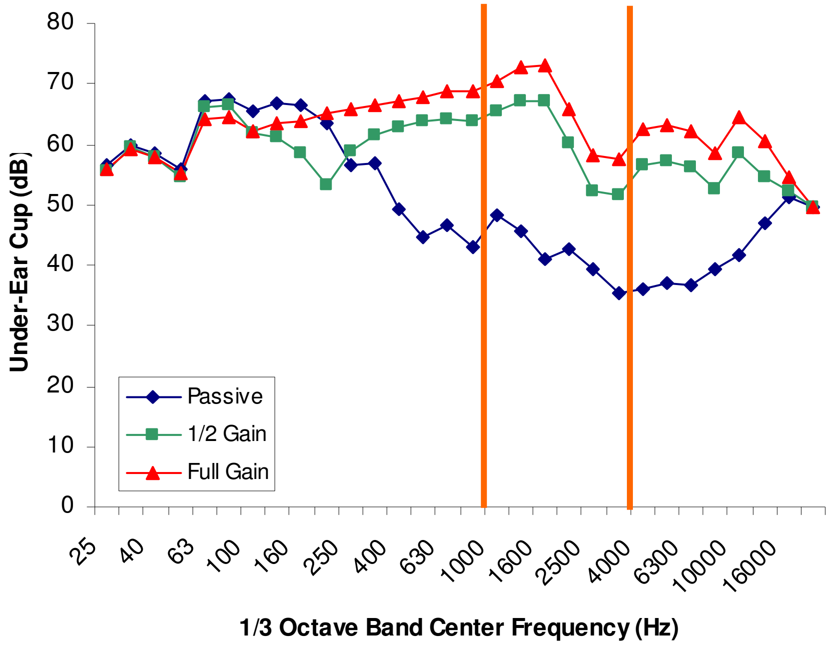

Figure 25c. Under-the-earcup spectra and noise levels for the Bilsom® Impact™ amplitude-sensitive earmuff within 90 dBA pink noise using an ATF. The vertical lines represent the frequency range for most warning signals, including backup alarms.

- Bilsom® Clarity™ C2. Figure 26 shows the Bilsom® Clarity™ C2, the passive counterpart to the Bilsom® Impact™. These two earmuffs have exactly the same designs except that one is a sound transmission device while this one is not. As such, these devices allowed a direct signal detection comparison to be made sound levels, for both normal and non-normal hearers, and between sound types. This device has an NRR of 23 (Bilsom® Clarity™ C2 user manual).

Figure 26. The Bilsom® Clarity™ C2 circumaural earmuff, passive counterpart to the Bilsom® Impact™, NRR = 23.

- <u>Peltor TacticalPro™.</u> According to the manufacturers, the Peltor TacticalPro™ is an active hearing protector that allows "comfortable contact with the surroundings while effectively protecting the user from harmful noise" (Peltor TacticalPro™ user manual). This device is shown in Figure 27. The attenuation characteristics of this HPD were also investigated at three different pink noise levels in the research work that utilized an acoustical test fixture (J.G. Casali and J.A. Lancaster, personal communications, May 2006), as described earlier. As for the Bilsom® Impact™, when the electronics are off, the HPD attenuates the noise as a passive HPD. When the electronics are on, the amplifiers amplify external signals (such as a backup alarm). This effect is illustrated in Figures 28a, 28b and 28c at the respective noise levels, which were gathered during the aforementioned Casali and Lancaster research (2006) utilizing an acoustical test fixture. At the 75 dBA external noise level, the sound heard around the peak back-up alarm frequency (1250 Hz) is amplified to 51 dBA when the HPD is at full gain, which is an amplification of 16 dBA when compared to when the electronics are turned off (see Figure 25a). As the pink noise is increased to 85 dBA, the under-earcup maximum slightly increases to 52 dBA at the reverse alarm frequency at the full gain setting (see Figure 25b). At the 90 dBA pink noise level, the under the ear-cup maximum increased to 54 dBA for the reverse alarm frequency at the full gain setting. Similarly, the speech frequencies (1-4 KHz) were also amplified. At the 75 dBA pink noise level at full gain setting, the dB linear sound level was 69 dBA. At the 85 dBA external noise level, the dB linear sound level slightly increased to 70 dBA. At the 90 dBA external noise level, the dB linear sound level slightly increased to a level of 71 dBA. As with observed o the Bilsom® Impact™ device, the device should not amplify sound more than it does in the 75 dBA and 85 dBA noise, but there either was some amplification and/or the 90 dBA noise simply overcame the muff's passive attenuation.

Figure 27. The Peltor TacticalPro™ sound transmission circumaural earmuff, NRR = 26.

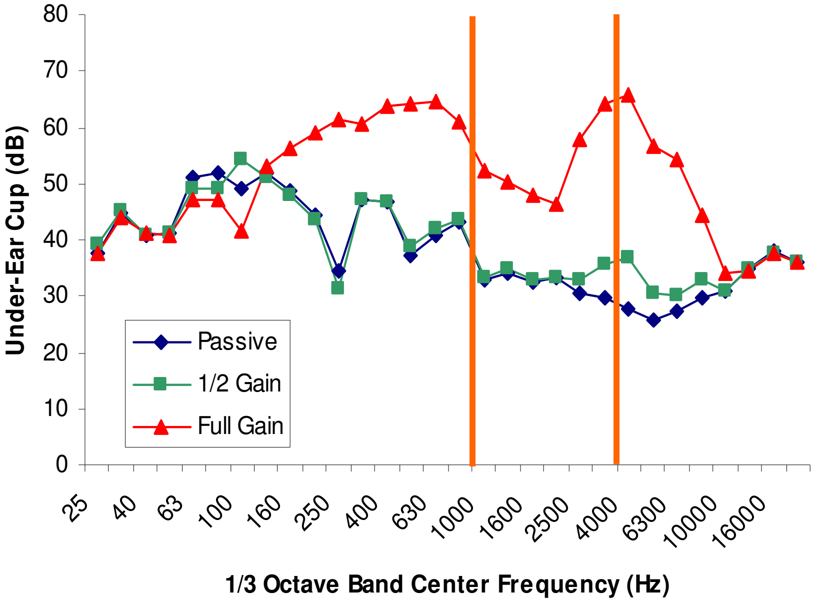

Figure 28a. Under-the-earcup spectra and noise levels for the Peltor TacticalPro™ amplitude-sensitive earmuff within 75 dBA pink noise using an ATF. The vertical lines represent the frequency range for most warning signals, including backup alarms.

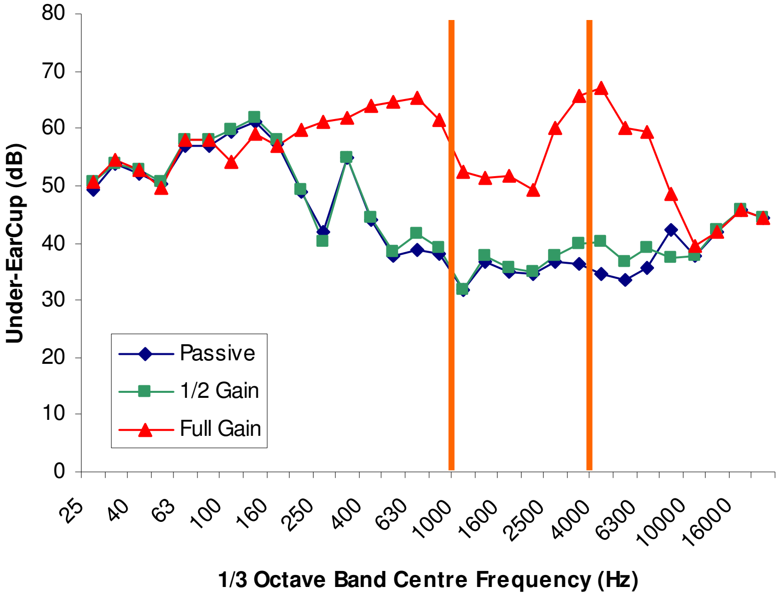

Figure 28b. Under-the-earcup spectra and noise levels for the Peltor TacticalPro™ amplitude-sensitive earmuff within 85 dBA pink noise using an ATF. The vertical lines represent the frequency range for most warning signals, including backup alarms.

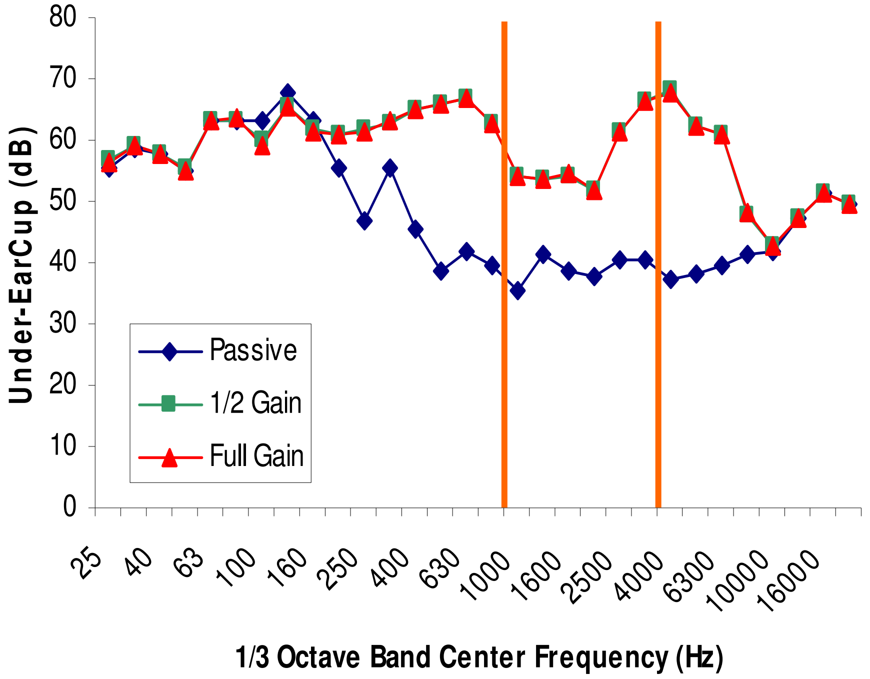

Figure 28c. Under-the-earcup spectra and noise levels for the Peltor TacticalPro™ amplitude-sensitive earmuff within 90 dBA pink noise using an ATF. The vertical lines represent the frequency range for most warning signals, including backup alarms.

- <u>Peltor H7™</u> Figure 29 shows the Peltor H7™ circumaural earmuff that was used as the passive counterpart to the Peltor TacticalPro™. These two earmuffs have the same NRR rating of 26 dB (Bose safety products website). This again allowed comparisons to be made between the Peltor TacticalPro™ and the Peltor H7™.

Figure 29. The Peltor H7™ passive circumaural earmuff, passive counterpart to the Peltor TacticalPro™, NRR = 26.

Balancing order of treatment

As a way to avoid order effects, all the experimental conditions (the three within-subject independent variables mentioned above) were presented in a counterbalanced manner using a Latin square design. The diagram for the Latin square design is shown in Appendix C. The section below explains the pros and cons of counterbalancing treatments.

Within subject variables, also known as repeated measures have many advantages that include:

1. Control for individual differences among subjects (often the largest source of variation).
2. More economical – fewer subjects needed.
3. Allow the study of a phenomenon across time, enabling the effects of learning, fatigue, forgetting, performance, aging, etc to be studied.

However, it is also important to note that repeated measures designs also have disadvantages associated with them. These include:

1. Carryover effects – treatments given earlier may influence those given later.

2. Practice effects – subjects get better at the task as a result of repeated trials in addition to the treatment (testing effect).
3. Fatigue – subjects' performance is adversely influenced by fatigue (or boredom).
4. Sensitization – subjects' awareness of the treatment is heightened because of repeated exposure (Dean and Voss, 1999).

As a way to control for these effects, it is important to implement a balancing procedure with respect to the order of treatments. Since this experiment was fairly complex (4 factors), with both within- and between- subject elements, the use of a balanced Latin square design was most appropriate and was applied. The diagram for the Latin square is shown in Appendix C.

Dependent Measures

Backup alarm masked threshold level. There were three dependent measures in this study. The first dependent measure was the backup alarm masked threshold level. Specifically, this dependent measure was the level of the alarm (dBA) at listeners' threshold, which constituted a *masked threshold* since all trials were in conditions of noise. The backup alarm signal that was used for this study was from a standard backup alarm that met the SAE J994b, and the ISO 7731 standards. This type of backup alarm enunciates at a peak frequency of 1250 Hz (see Figure 30), and produces an overall level of 97 dBA (with a user-adjustable additional setting of 97 dBA — 107 dBA; 107 dBA is the level currently used by large equipment manufacturers) (John Deere, Inc., personal communication, 2006). Such an alarm has been used in other studies, such as the previously discussed research conducted by Casali et al. (2004) that investigated the detectability of backup alarms in noisy environments while listeners were wearing ANR and passive HPDs.

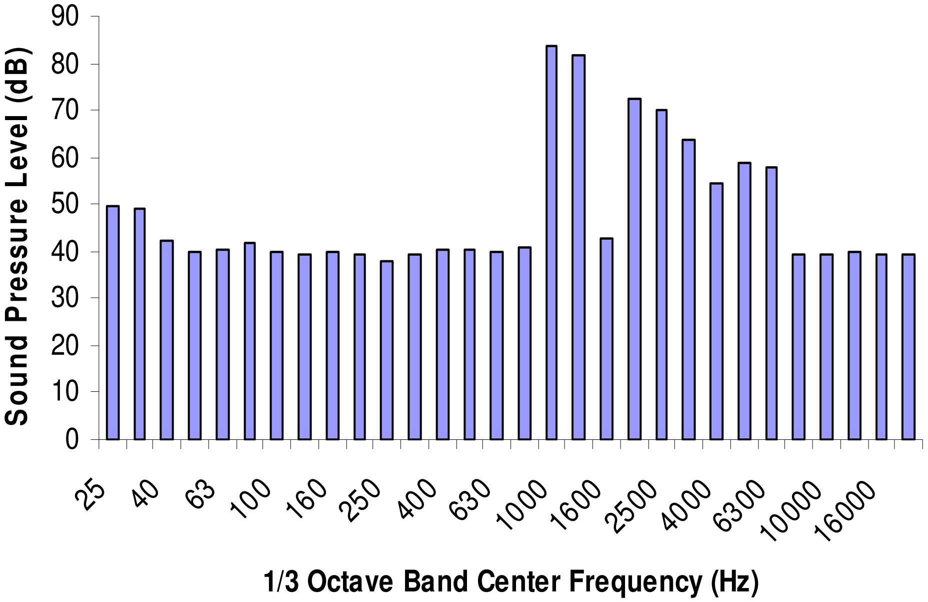

Figure 30. Backup alarm spectrum as used in the experiment. Note the peak energy at 1250 Hz, which is the backup alarm primary frequency, and the secondary energy at 2500 Hz.

Alarm detectability. The second dependent measure was alarm detectability. A 7-point semantic differential scale was used to determine participants’ *perceived* ability to detect the alarm under each headset (see Appendix A). This scale was administered to participants after the completion of each experimental condition.

Hearing protector comfort. The third and final dependent measure was hearing protector comfort. Other than the above-mentioned dependent measures, comfort can also be an important factor in determining the amount of protection provided by a HPD (Park & Casali 1991; Casali, Lam, and Epps, 1987). A HPD that is uncomfortable will result in a worker repeatedly taking the device off and putting the device on again, which will result in reduction in attenuation. For instance, if an HPD with NRR of 25 dB is not worn for 15 minutes out of an 8-hour work period, then the resultant ‘time corrected NRR’ will be 20 dB (Park & Casali, 1991). For these reasons, a *subjective rating scale,* namely an *Osgood semantic differential scale*, is justified as a means of determining comfort by a sample of participants; such scales are often used (Wright, 1993) to collect information. Casali et al. (1991) developed a rating scale for HPD comfort, which has been validated by many other studies (Casali, 1992; Park and Casali, 1991) and was used in this study. This Osgood semantic differential scale is a multidimensional, bipolar descriptor comfort rating scale that consists of 12 seven-step bipolar adjective items, and is shown in Appendix B.

Apparatus

All hardware for the experiment was housed, and all experimental testing was conducted, in the Auditory Systems Lab's Large-Scale Acoustical Test Facility, which is located in room 519N Whittemore Hall on the campus of Virginia Tech. The room was tested for diffusivity and non-directionality around the subject's head (seated location) at six different positions per ANSI S3.19-1974. The criteria require that the maximum absolute value dB difference between all the six microphone positions be less than 2 dB. The room met the criteria, except for the up-down positions, which were compensated by using a chair that could be altered for height (up and down positions); results are shown in Table 4.

Table 4. The backup alarm test signal, originating at 40 dB broadband, at six positions about head positions

1/3 OB Center (HZ)	Right (-15,0,0)	Left (15,0,0)	R-L Δ*	Up (0,0,15)	Down (0,0-15)	Front (0,15,0)	Back (0,-15,0)	6 Position Δ**
125	40	39.9	0.1	39.9	39.9	39.9	39.8	0.2
250	39.8	39.7	0.1	39.9	39.9	39.9	39.7	0.2
500	39.8	39.7	0.1	39.8	39.8	39.8	39.8	0.1
1000	65.1	64.2	0.9	55	61.5	57.4	59.6	10.1
2000	51.1	51	0.1	40.4	44.4	46	50.1	10.7
3150	43.8	43.1	0.7	42.9	44.5	43	44.4	1.6
4000	40	40	0	40	39.9	40.1	40.1	0.2
6300	40.1	39.8	0.3	39.9	40.3	39.9	40.6	0.8
8000	39.8	39.8	0	39.8	39.8	39.8	39.8	0

* Absolute value dB difference between right and left microphone position.
** Maximum absolute value dB difference between all pairs of the six microphone positions.

A backup alarm signal wave file was used as the signal source, and was presented to the participants through a Klipsch K-57K horn loudspeaker positioned behind the seated subject, itself amplified by a Sony STR DE 135 amplifier. The Masking noise was presented to the subject through four Infinity SM-155 loudspeakers, positioned at four equidistant locations from, and positioned facing, the seated participants, as shown in Figure 31 below. To verify that each speaker produced the same noise intensity to the seated participant, a Larson-Davis model 2559 1/2-inch microphone (connected to a Larson-Davis Spectrum analyzer model 2800B) was used to measure and verify the output of each speaker (see Figure 31 below). At the beginning of each session each day, a Quest QC-20 calibrator was used to calibrate the Larson-Davis Spectrum analyzer and its microphone, at 94 dBA at 1 kHz. The loudspeakers were also powered by a separate Sony STR DE-135 amplifier, and their output levels were verified using the microphone to present the required intensity as measured using the Larson-Davis 2800B real-time spectrum analyzer.

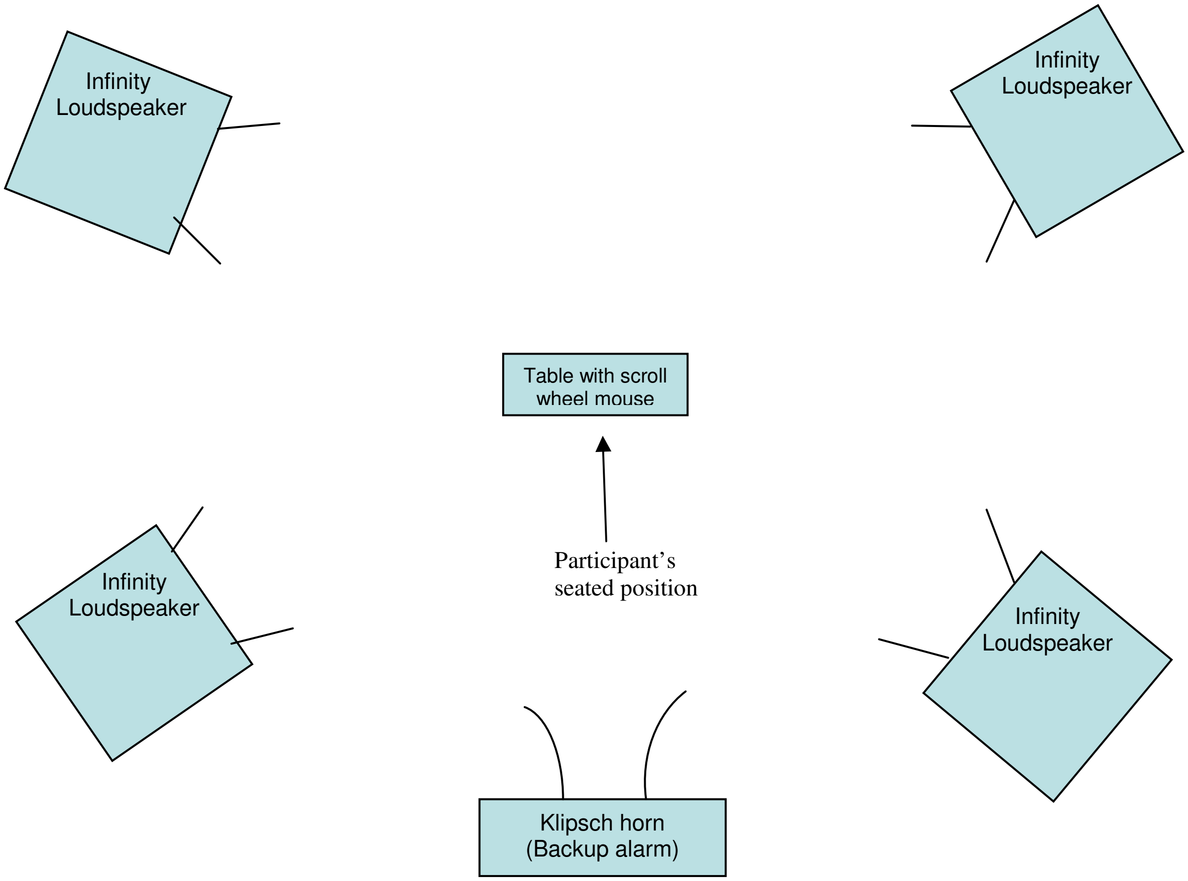

Figure 31. Experimental setup.

Figure 32 shows the instruments located at the experimenter's station. A laptop computer with Labview version 8.0 software installed was configured to track and record the participants' responses using scroll wheel of a Microsoft laser wireless mouse.

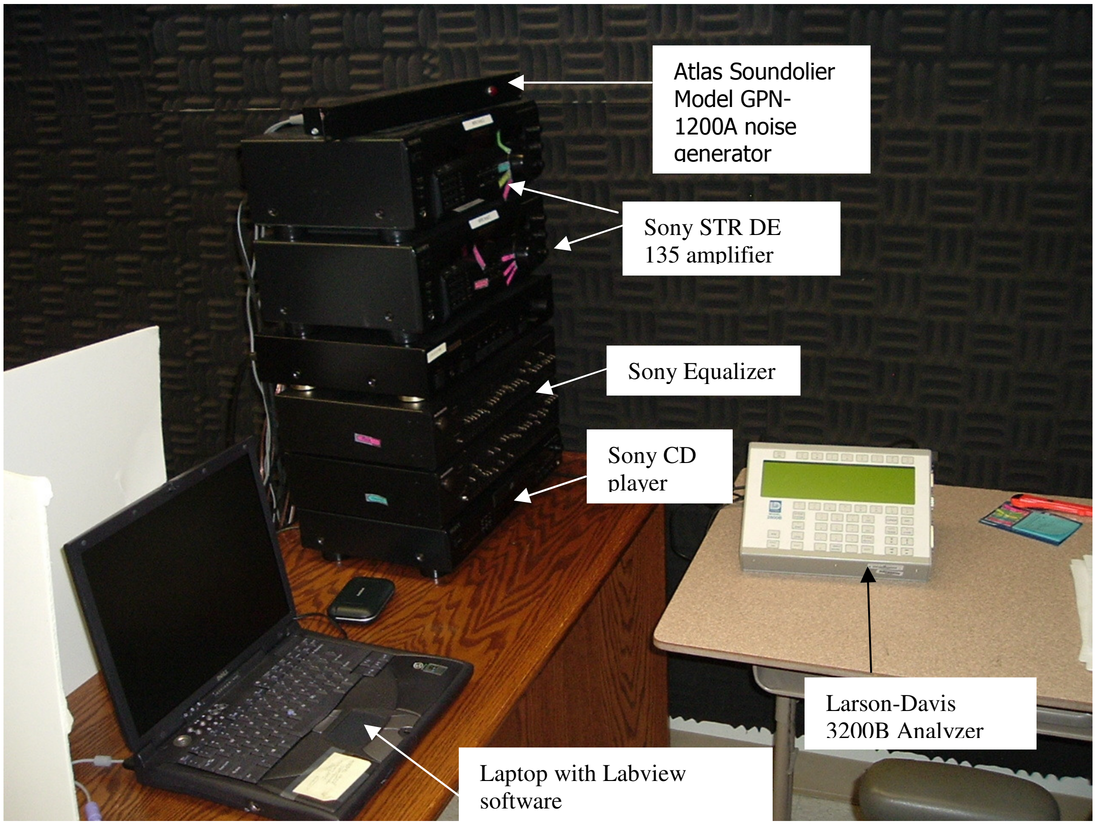

Figure 32. Instrumentation at the experimenter's position.

Procedure

Screening session. Participants reported to Whittemore 519N for all screening sessions. Participants first had to undergo an otoscopic inspection of their ears before the hearing test to ensure that there were no foreign objects or impacted cerumen that might affect their thresholds. Participants then underwent an audiogram to determine hearing thresholds for comparisons to the criteria specified previously. Then, according to the Latin-Square ordering, one of the four HPDs was experimenter-fitted to ensure that a proper and consistent fit could be realized. One HPD was tested in all noise level and type conditions in each session, Appendix D fully describes all step involved in this session.

After successful completion of the audiometric screen, participants were instructed in and practiced the threshold task. To do so, participants were given a Peltor H-10A, high-attenuation circumaural earmuff (i.e., a different device than those in experimental design), which was fitted by the experimenter. Masking noise was presented in the form of a Caterpillar tractor in operation (Network Sound Effects, Vol. 5, Track #19) at 95 dBA, and participants tracked a 2 KHz pure-tone using the mouse/scroll-wheel. Participants performed the "Békésy" tracking by increasing and decreasing the backup alarm intensity. The intensity resolution that was measurable by this instrumentation was approximately one dB.

1. Participants first rolled the scroll wheel forward to turn the backup alarm volume up to a level where they were completely sure that they could hear the alarm.
2. Then, participants rolled the scroll wheel backwards, reducing the level until they no longer could hear the backup alarm.
3. They then turned the backup alarm volume up again, this time to a level they could just barely hear the alarm.
4. Then, they turned the volume down again to a level where they could no longer hear the alarm.
5. Steps 2-4 continued for 30 seconds, resulting in approximately six 'excursions' between being able to 'just barely hear' and 'not be able to hear' the backup alarm signal.

At the end of the 30 second time period, performance was determined as "sufficient" if the tracking was consistent over five trials; the masked threshold was defined as the level at which the signal was heard/not heard within two dBA, which corresponded to five 'units' of mouse detents across all trackings. For an acceptable response, a number of factors were taken into account. Firstly, the oscillations in tracing consisted of at least six excursions per experimental trial. Also, the first excursion for a given tracing response was not included in the masked threshold calculation, as participants were instructed to increase the initial stimulus intensity until they were absolutely sure that they could hear the signal, as opposed to threshold detection of the signal in subsequent presentations. In addition, a tracking that had a valley exceeding a "peak" was eliminated. These criteria for scoring masked thresholds also were applied to the experimental trials, the discussion of which follows.

Experimental sessions. Each headset type was tested on different days, with all levels of Masking noise and each Masking noise Type presented on each day, and according to the Latin square design. For each session, the experimenter fit the headset to be tested as a way to increase consistency in the HPD fit across participants. A table was located in front of the participant, and on the table was the mouse that was used for tracking the backup alarm. A string with a fixated object at the bottom end i.e., a plumb bob hung from the ceiling to the participant's nose level. The participant sat in the experimental chair facing a table, with a distance of about 2 inches between the participant's nose and the plumb bob this is illustrated in Figure 33. A height adjustable chair was used to sit participants during the experiment so that the nose level of each participant was at the plumb bob level.

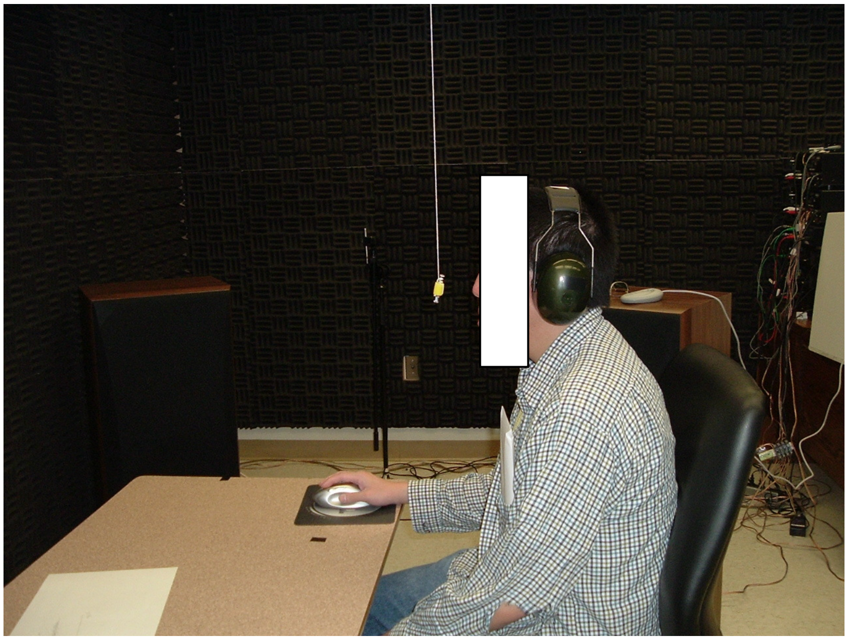

Figure 33. A participant during an experimental trial sitting upright with nose level about 2inches from the plumb bob**.**

Only the "full-gain" setting was utilized for each sound transmission device; the setting (as described earlier) was taped in that position to disallow tampering. Masking noise was verified at the listener's seated position located by a plumb bob (centered over the chair, as illustrated in Figure 33), using the sound measurement equipment described earlier.

In each experimental trial, the participants listened for and adjusted the backup alarm intensity using the mouse/scroll wheel (via the process described earlier), which was set to actuate in approximately 1 dB steps. The detent increments of the mouse scroll wheel were not exactly in 1 dB steps due to software constraints; however, the intensity at each detent was measured and, since the actual difference between detents was determined, participants' choices with respect to their backup alarm masked threshold using the scroll wheel could be ascertained in approximately 1 dB steps. Each 30-second trial, i.e., wearing a specific HPD at a specific masking noise level, and a specific masking noise type (for example the Bilsom® Impact™ HPD at 75 dBA with pink noise as the masking noise type) consisted of five trials. This gave a total of

40 trials per HPD. Participants were given 30 seconds to complete the tracking task for each Masking noise variable (i.e., type and level) using a particular HDP. At the completion of testing for a particular experimental condition , participants were given the semantic differential scale to rate their ability to detect the backup alarm with the HPD used, followed by the comfort rating scale to elicit their subjective impressions regarding comfort of the HPD.

DATA REDUCTION

Calculation of Masked Threshold

As mentioned earlier, Labview software was used to capture the raw numerical data of the masked threshold values. The raw data were then exported into a Microsoft excel file, where they were graphed. The graphed data for all of the noise levels (75, 85, 95 and 105 dBA) maintained a scale that ranged from 0-50 with one unit increments; this scale corresponded to the number of scroll wheel detents that were used for the Békésy tracking. The "0" value on the scale represented the minimum scroll wheel detent position (zero) on the mouse, and "50" represented the maximum number of scroll wheel detents (50) on the mouse. Separate scales were created for each Masking noise level (75, 85, 95 and 105 dBA), which represented the dBA value at each scroll wheel detent. The intensity values (dBA) were then determined by equating the maximum and minimum levels on the 0-50 scale to the new dBA scale. Masked threshold values (dBA) for each trial were then determined by calculating the mean values of the peaks and troughs for each oscillating "zig-zag like response" function that was traced by the participant for a given condition. However, the first excursion for a given tracing response was not included in the masked threshold calculation as participants were instructed to increase the initial stimulus intensity until they were absolutely sure that they could hear the signal, and to decrease the stimulus intensity until they were absolutely sure that they could not hear the signal, as opposed to threshold detection or loss of detection of the signal subsequent presentations. Thus, each maximum peak corresponded to a minimum trough such that an equal number of peaks and troughs were realized. The position of this mean value (Y-axis) over the 30 second measurement interval defined the value of masked threshold, as shown in Figure 34; in this example, the mean masked threshold value was 17.2 dBA.

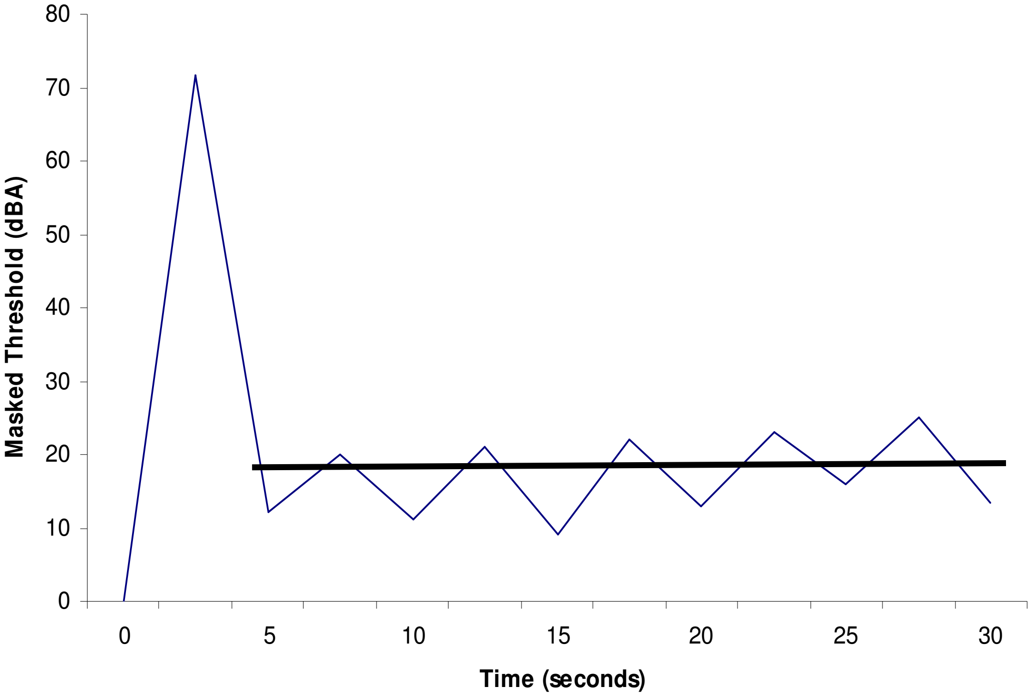

Figure 34. Threshold tracking example, with midline between peaks and troughs.

DATA ANALYSIS AND RESULTS

The Statistical Analysis Software (SAS) was used for all the statistical data analysis, and Tukey's Studentized Range (HSD) test was used for all post-hoc analysis.

Threshold tracking results were analyzed using a four-way analysis of variance (ANOVA) to test for significance at an alpha level of 0.05, with three within-subject factors and one between subject factor (hearing ability) . The main effects were hearing ability (HA), hearing protection device (HPD), Noise Level (NL), Noise Type (NT), and all of the associated interactions. Table 5 summarizes these results.

For the main effects, the Least Square-mean (LS-Mean) values were used instead of the regular arithmetic mean values because this allowed a comparison of means between unequal sample sizes, in this case normal hearers ($n = 8$) and non-normal hearers ($n = 3$), to be made. By definition, LS-means are predicted population margins, i.e., they predict the estimated marginal means over a balanced population. In other words, LS-means are to unbalanced designs as the arithmetic means are to balanced designs (Searle, Speed, and Milliken, 1980).

TABLE 5.ANOVA Summary tables for primary (Main) analysis (**bold** values indicate statistical significance at $p<0.05$).

Source	**DF**	**ANOVA SS**	**MS**	***F* Value**	**Pr > *F***
Between-Subjects					
Hearing Ability (HA)	1	6534.4950	6534.4950	622.50	**<.0001**
S/HA	20	209.9436	10.4972		
Within-Subjects					
Hearing Protector Device (HPD)	3	665.3798	221.7933	21.13	**<.0001**
HA X HPD	3	29.1348	9.7116	0.93	0.429
HPD X S/HA	60	626.5555	10.4426		
Noise Level (NL)	3	35923.8027	11974.6009	1140.74	**<.0001**
HA X NL	3	195.2749	65.0916	6.20	**0.0004**
NL X S/HA	60	629.9190	10.4987		
Noise Type (NT)	1	7.3892	7.3892	0.70	0.4022
HA X NT	1	0.6605	0.6605	0.06	0.8021
NT X S/HA	20	220.1733	11.0087		
NT X HPD	3	4.1228	1.3743	0.13	0.9417
HA X NT X HPD	3	1.1222	0.3741	0.04	0.991
NT X HPD X S/HA	60	561.0900	9.3515		
NT X NL	3	18.0131	6.0044	0.57	0.6339
HA X NT X NL	3	7.7058	2.5686	0.24	0.8651
NT X NL X S/HA	60	642.1500	10.7025		
HPD X NL	9	150.1193	16.6799	1.59	0.1179
HA X HPD X NL	9	18.4444	2.0494	0.20	0.9946
HPD X NL X S/HA	180	1844.4330	10.2469		
NT X HPD X NL	9	48.1440	5.3493	0.51	0.8673
HA X NT X HPD X NL	9	39.6105	4.4012	0.42	0.9244
NT X HPD X NL X S/HA	180	1886.2157	10.4790		
Total	703	50263.8991			

Masked Threshold

The ANOVA revealed a significant main effect of hearing ability (HA) on masked threshold, $F(1,20) = 622.5$, $p < 0.0001$, with the LS-mean threshold values for normal hearers and non-normal hearers as 73.8 dBA and 83.5 dBA, respectively. Non-normal hearers required almost 10 dBA in additional backup alarm intensity before the signal was detected. These values are illustrated in Figure 35.

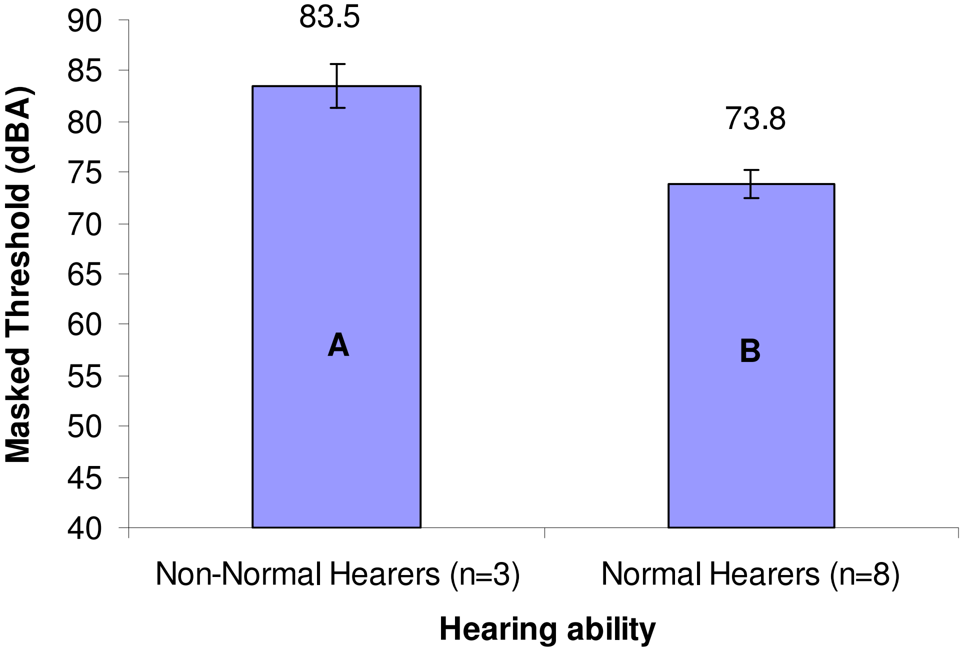

Figure 35. Effect of hearing ability on masked threshold with 95% confidence interval plotted. Means with the same letter are not significantly different ($p \leq 0.05$).

The ANOVA revealed a significant main effect of HPD on masked threshold $F(3,60) = 21.1$, $p < 0.0001$, with the LS-means ranging from 77.1 dBA for the Bilsom® Clarity™ C2 to 80.5 dBA for the Bilsom® Impact™, as illustrated in Figure 36. Post hoc analysis using the Tukey's Studentized Range (HSD) test indicated that the use of the two sound transmission devices—the Bilsom® Impact™ and the Peltor TacticalPro™ resulted in higher masked threshold values (80.5 dBA and 79.8 dBA, respectively) than did their passive counterparts, the Bilsom® Clarity™ C2 and the Peltor H7™ (77.1 dBA and 77.3 dBA, respectively). The passive headsets resulted in an *improved* ability to detect the backup alarm when compared to the sound transmission headsets, which required higher levels for detection. This suggests that the sound transmission devices amplified <u>both</u> the signal <u>and</u> the noise, thereby affecting the ability of listeners to detect the backup alarm in noise when compared to the passive headsets.

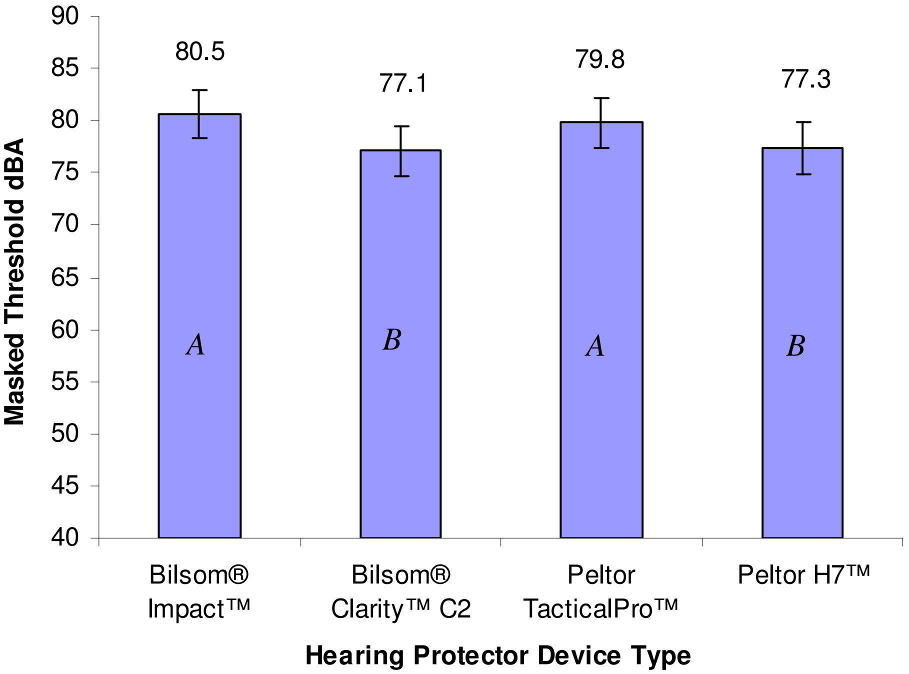

Figure 36. Effect of hearing protection device type on masked threshold with 95% confidence interval. LS-Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

ANOVA revealed a significant main effect of noise level (NL) on masked threshold, $F(3,60) = 1140.7$, $p < 0.0001$, with the LS-means ranging from 92.7 dBA for the 105 dBA Masking noise, to 65.0 dBA for 75 dBA Masking noise (see Figure 37). The 105 dBA Masking noise had highest masked threshold values, while the 75 dBA Masking noise had the lowest masked threshold. As anticipated, masking noise level directly affected the masked threshold values in a systematic statistically significant manner—the higher the masking noise, the higher the masked threshold value. This effect is illustrated in Figure 37, and is in agreement with the study by Hawkins and Stevens (1950).

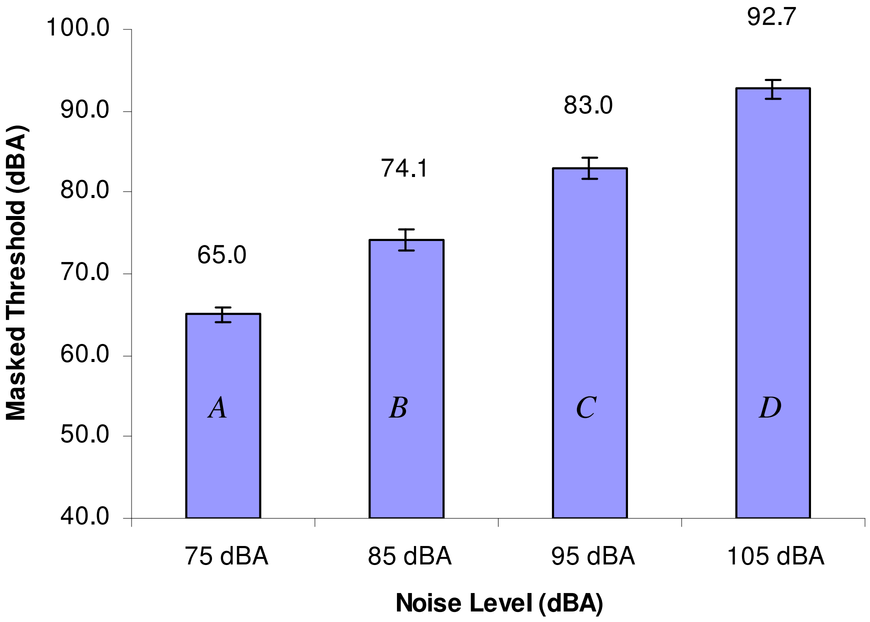

Figure 37. Effect of Noise Level (NL) on masked threshold with 95% confidence interval. LS-Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

There was a significant interaction between HA and NL, $F(3,60) = 6.2$ $p <$ 0.0004, this is ilustrated in Figure 38. Post hoc analysis for the interaction of Noise Level (NL) and Hearing Level (HL) showed that non-normal hearers had a statistically higher masked threshold values across all noise levels than the normal hearers. This is shown in Figure 38. This makes sense since non-normal hearers (with elavated hearing loss) are expected to perceive signals at a higher level, hence higher masked threhold values compared to normal hearers.

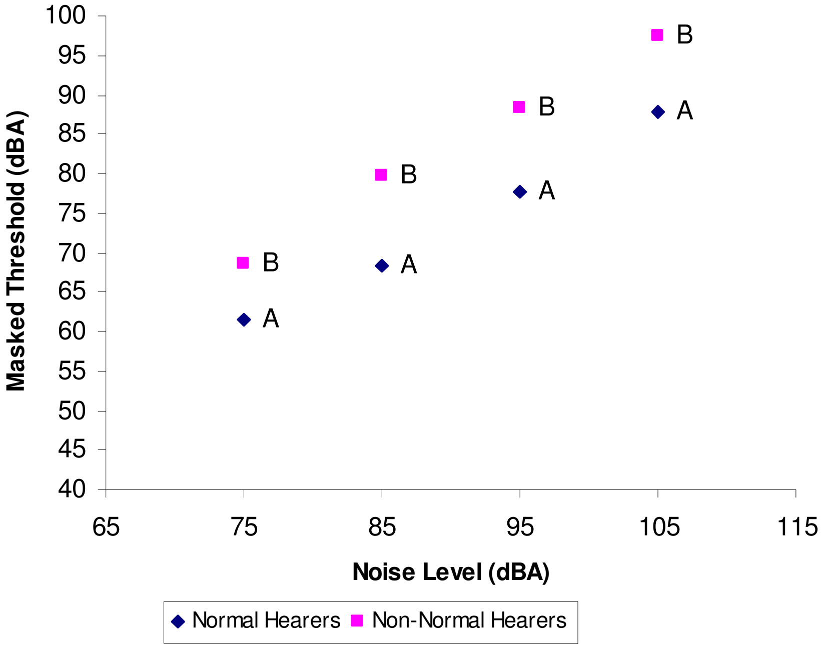

Figure 38. Interaction of Noise Level (NL) and Hearing Ability (HA).

The ANOVA did not show any significant differences of the Masking noise Type, i.e., pink noise and milling machine noise, with means of 78.5 dBA and 78.8 dBA, respectively (see Figure 39). These results can be attributed to the effects of masking. The spectrum of a 1994 CMI PR-500B milling machine (Figure 23b) shows high levels of lower frequency noise, hence increasing the possibility of upward spreading of masking. However, the levels of masking for both the pink spectrum and the milling machine spectrum were essenstially the same across the noise levels of the experiment.

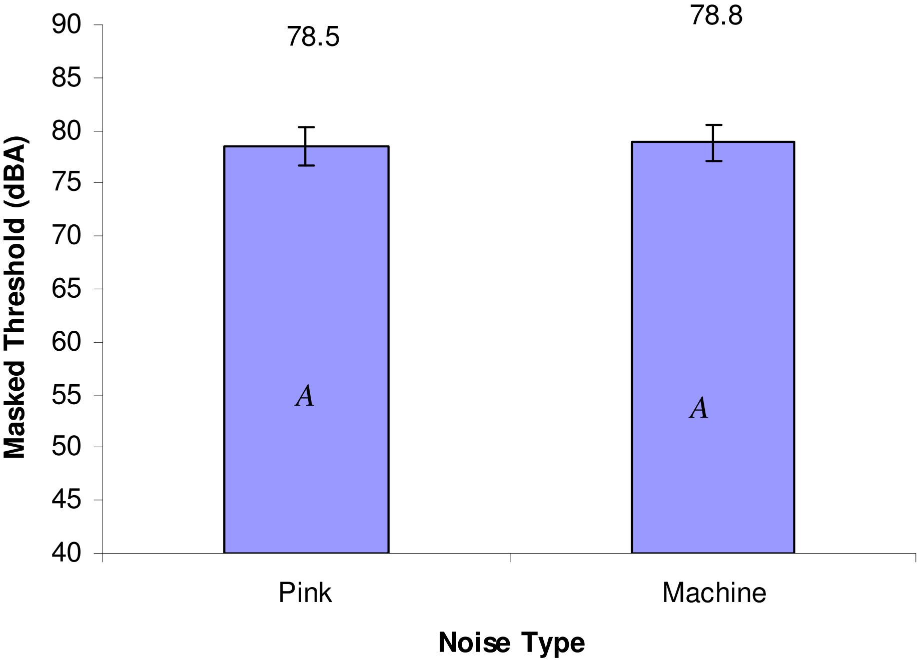

Figure 39. Effect of Noise Type (NT) on masked threshold on masked threshold with 95% confidence interval. LS-Means with the same letter are not significantly different (*p* ≤ 0.05).

*Interaction of HPD and NL.*Although ANOVA did not show any significant interaction of HPDs and NL, a post hoc analysis was done. This interaction was a priori since past research, such as that done by Casali et al., (2004) revealed that the performance of HPDs vary with different noise levels. Results from the post hoc analysis are shown in Figure 40.

At the 75 dBA masking noise level, Tukey's Studentized Range (HSD) test indicated that the Bilsom® Clarity™ C2 had a statistically significantly lower masked threshold value (61.3 dBA) than the Bilsom® Impact™ (65.7 dBA). These results suggest that at the 75 dBA masking noise level, participants found it more difficult to perceive the backup alarm while wearing the Bilsom® Impact™ earmuff compared to the Bilsom® Clarity™ C2 device.

At the 85 dBA masking noise level, post hoc analysis using the Tukey's Studentized Range (HSD) test indicated that the Peltor H7™ had a statistically significantly lower masked threshold value (69.1 dBA) than the Bilsom® Impact™ (73.8 dBA). These results suggest that at the 85 dBA masking noise level, participants found it *easier* to perceive the backup alarm while wearing a passive device (Peltor H7™) than a sound transmission device (Bilsom® Impact™).

At the 95 dBA masking noise level, post hoc analysis using the Tukey's Studentized Range (HSD) test indicated that the Peltor H7™ and Bilsom® Clarity™ C2 devices had significantly lower masked threshold values (78.4 dBA and 79.5 dBA respectively) than the Peltor TacticalPro™ and the Bilsom® Impact™ that both had a masked threshold value of 82.1 dBA. Again, this suggests that at the 95 dBA noise levels, participants could perceive the backup alarm easier while wearing passive devices than the sound transmission devices.

At the highest masking noise level (105 dBA) post hoc analysis using the Tukey's Studentized Range (HSD) test did not show any statistical significance across HPDs.

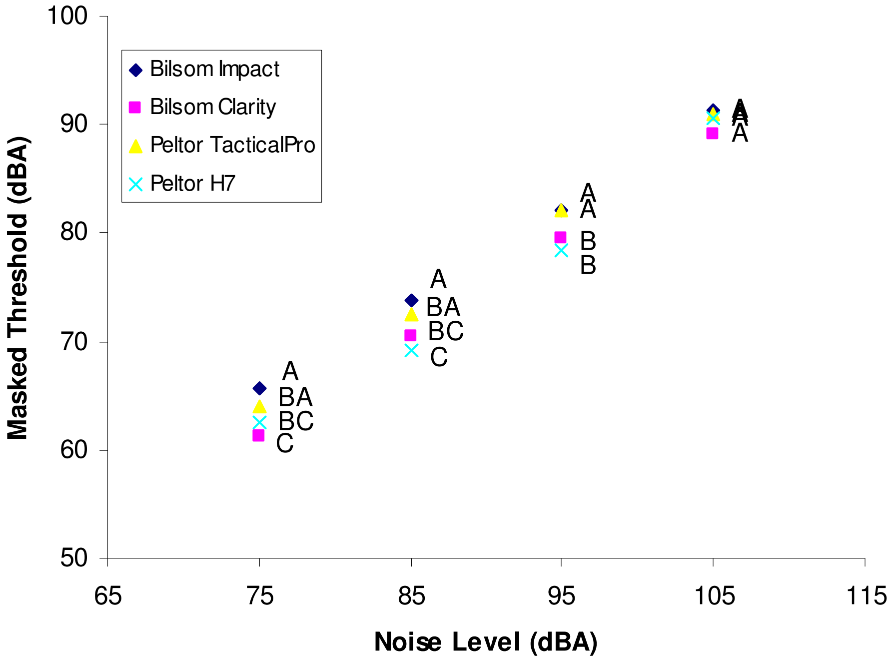

Figure 40. Interaction of hearing protection device type and noise level on masked threshold. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

Simple Effects,Normal hearers. Subsequent ANOVA revealed that there was a simple effect of HPD on masked threshold for normal hearing individuals in 75 dBA noise, $F(3,56) = 5.4$, $p < 0.0024$, ANOVA summary table shown in Table 6.

TABLE 6.ANOVA Summary tables for normal hearing individuals in 75 dBA noise level. (**bold** values indicate significance).

Source	DF	ANOVA SS	MS	F Value	Pr > F
HPD	3	147.7967	49.2656	5.42	**0.0024**
NT	1	11.8164	11.8164	1.30	0.2590
HPD X NT	3	24.3692	8.1231	0.89	0.4500
HPD X NT X S/HA	56	508.8000	9.0900		
Total	63	692.8000			

Post hoc analysis using the Tukey's Studentized Range (HSD) test indicated that the Bilsom® Impact™ had a significantly higher masked threhold value of 63.8 dBA than the two passive devices Bilsom® Clarity™ C2 and Peltor H7™ (59.7 dBA and 60.9 dBA respectively). The masked threshold values for Peltor TacticalPro™ device did not differ from any of the devices. These results suggest that normal hearers at the 75 dBA masking noise level might find it more difficult to perceive the backup alarm while wearing the Bilsom® Impact™ earmuff compared to the passive devices. There was about a 3 dB mean difference in masked threshold values between the Bilsom® Impact™ device and the passive devices, and these results are illustrated in Figure 41.

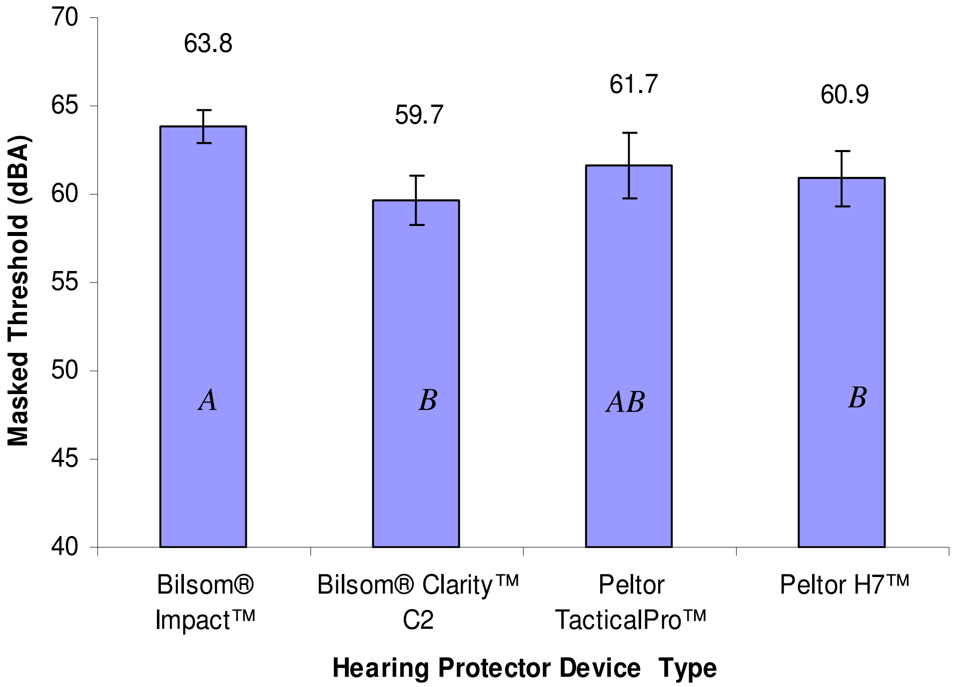

Figure 41. Effect of hearing protection device type and noise level on masked threshold for normal hearers at 75 dBA with 95% confidence interval. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

All other Masking noise levels above 75 dBA (i.e., 85, 95, or 105 dBA) for normal hearers did not result in significant differences across HPDs in masked threshold values. The 85 dBA masking noise level revealed nonsignificant differences for the masked threshold values across all HPDs, with means of 70.4 dBA, 67.7 dBA, 69.2 dBA and 66.2 dBA for the Bilsom® Impact™, Bilsom® Clarity™ C2, Peltor TacticalPro™ and Peltor H7™ respectively . The results are illustrated in Figure 42.

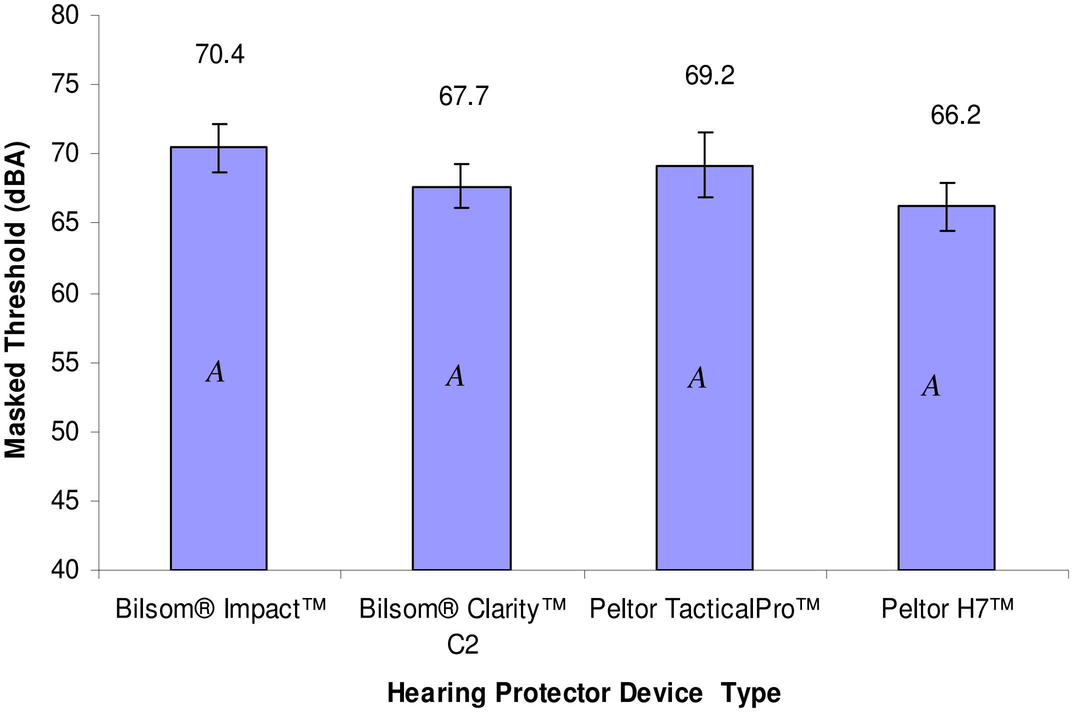

Figure 42. Effect of hearing protection device type and noise level on masked threshold for normal hearers at 85 dBA with 95% confidence interval. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

The 95 dBA noise level also resulted in nonsignificant differences for the masked threshold values of Bilsom® Impact™ (78.9 dBA), Bilsom® Clarity™ C2 (76.8 dBA), Peltor TacticalPro™ (79.2 dBA) and Peltor H7™ (75.5 dBA), with the results shown in Figure 43.

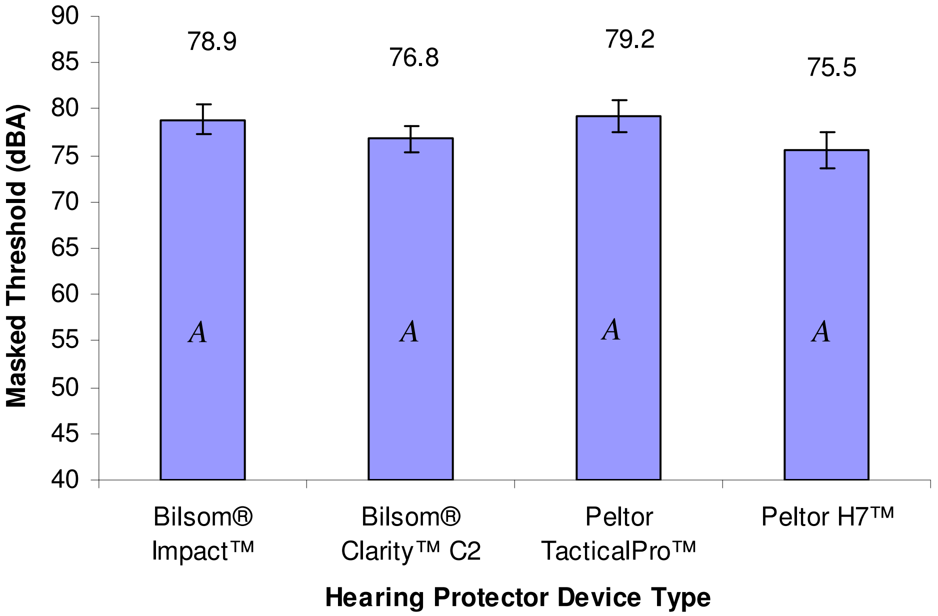

Figure 43. Effect of hearing protection device type and noise level on masked threshold for normal hearers at 95 dBA with 95% confidence interval. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey’s test.

The 105 dBA noise level also resulted in nonsignificant differences for the masked threshold values of Bilsom® Impact™ (88.9 dBA), Bilsom® Clarity™ C2 (86.8 dBA), Peltor TacticalPro™ (88.1 dBA) and Peltor H7™ (87.8 dBA); results are shown in Figure 43.

The results for the 85 dBA, 95 dBA and 105 dBA noise levels for normal hearers, all consistently show nonsignificant differences of masked threshold values for the Bilsom® Impact™, Bilsom® Clarity™ C2, Peltor TacticalPro™ and Peltor H7™ devices. This implies that for normal hearing individuals and at these noise levels, none of the devices in question would have an advantage over the other in terms of signal detection.

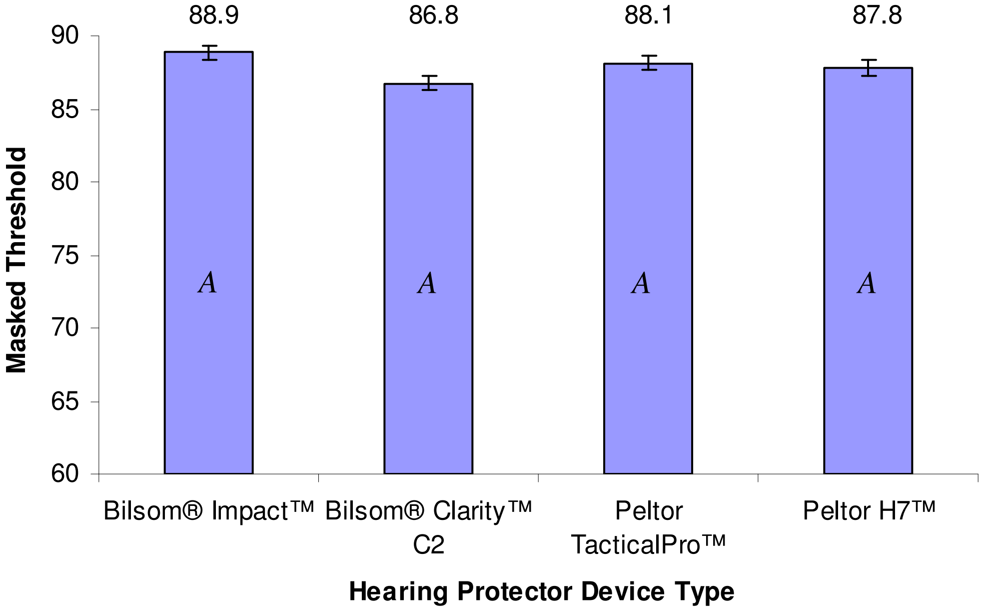

Figure 44. Effect of hearing protection device type and noise level on masked threshold for normal hearers at 105 dBA with 95% confidence interval. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

Simple Effects Non-normal hearers. ANOVA revealed a simple effect of HPDT on masked threshold for non-normal hearing individuals in the 75 dBA Masking noise, $F(3,16) = 9.9$, $p < 0.0006$. ANOVA results are shown in Table 7.

TABLE 7.ANOVA Summary tables for non-normal hearing individuals in the 75 dBA noise level. (**bold** values indicate significance).

Source	DF	ANOVA SS	MS	*F* Value	Pr > *F*
HPD	3	100.0346	33.3449	9.89	**0.0006**
NT	1	0.1204	0.1204	0.04	0.8525
HPD X NT	3	11.4513	3.8171	1.10	0.3659
HPD X NT X S/HA	16	54.0000	3.4000		
Total	23	165.6000			

Post hoc analysis revealed that the Bilsom® Impact™ headset had a significantly higher masked threshold value of 70.8 dBA compared to the two passive devices, Bilsom® Clarity™ C2 (65.8 dBA) and Peltor H7™ (67.4 dBA). Also, the Peltor TacticalPro™ (70.2 dBA) device did not differ from both the Bilsom® Impact™ (70.8 dBA) and Peltor H7™ (67.4 dBA), whilst the Bilsom® Clarity™ C2 device had a significantly lower masked threshold value than both the Bilsom® Impact™ and Peltor TacticalPro™ devices (see Figure 45). From a practical standpoint, this follows that at the 75 dBA for non-normal hearers, the passive device (specifically the Bilsom® Clarity™ C2) is a better device for signal detection than the two amplitude sensitive devices tested in this study.

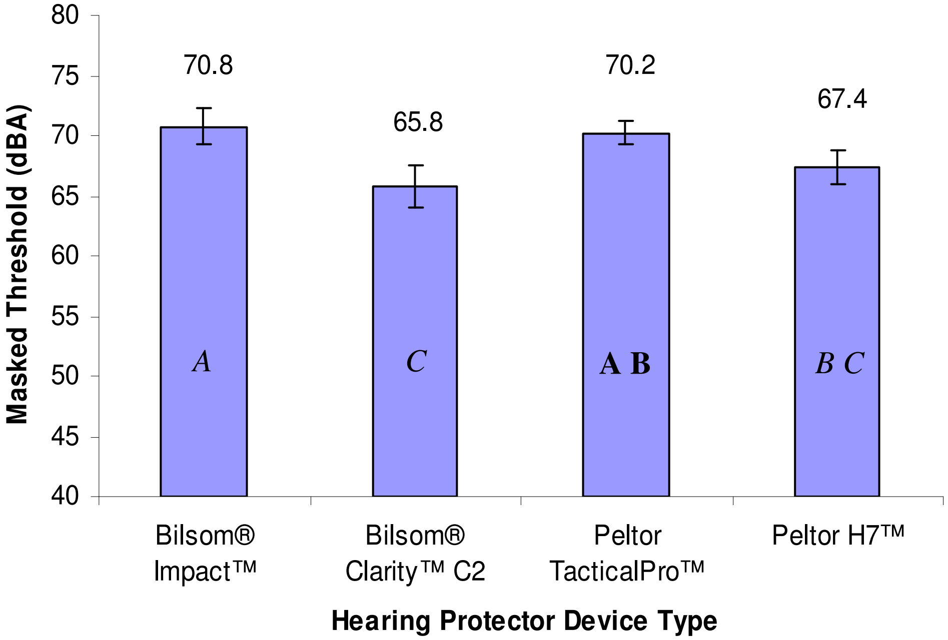

Figure 45. Effect of hearing protection device type on masked threshold for non-normal hearers at 75 dBA with 95% confidence interval. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

In the 85 dBA Masking noise, ANOVA revealed a simple effect of HPDT on masked threshold values, *F* (3, 16) = 15.5, *p* < 0.0001. ANOVA results are shown in Table 8.

TABLE 8.ANOVA Summary tables for non-normal hearing individuals in the 85 dBA noise level. (**bold** values indicate significance).

Source	DF	ANOVA SS	MS	F Value	Pr > F
HPD	3	158.4483	52.8000	15.50	**0.0001**
NT	1	2.5350	2.5350	0.70	0.4010
HPD X NT	3	2.5883	0.9000	0.25	0.8578
HPD X NT X S/HA	16	54.4867	3.4000		
Total	23	218.0583			

Post hoc analysis indicated that the two sound transmission devices (the Bilsom® Impact™ and Peltor TacticalPro™) had significantly higher masked threshold values of 82.9 dBA and 81.7 dBA, respectively, than did the passive devices, i.e., Bilsom® Clarity™ C2 (77.7 dBA) and Peltor H7™(76.8 dBA). This is shown in Figure 46. These results imply that in the 85 dBA Masking noise level, non-normal hearers could perceive the backup alarm at a lower masked threshold value, hence better signal detection, while wearing the passive devices (Bilsom® Clarity™ C2 and Peltor H7™) than the amplitude sensitive devices (Bilsom® Impact™ and Peltor TacticalPro™).

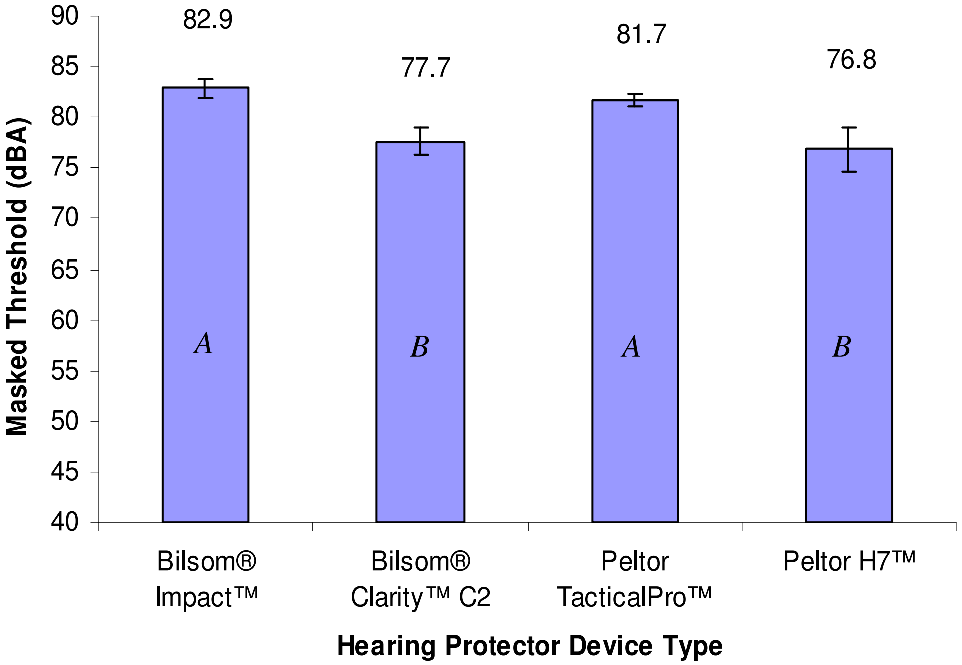

Figure 46. Effect of hearing protection device type on masked threshold for non-normal hearers at 85 dBA with 95% confidence interval. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

In the 95 dBA noise level, ANOVA revealed a simple effect of HPD on masked threshold values for the non-normal hearers, $F(3,16) = 31.4$, $p < 0.0031$. ANOVA results are shown in Table 9.

TABLE 9.ANOVA Summary tables for non-normal hearing individuals in the 95 dBA noise level. (**bold** values indicate significance).

Source	DF	ANOVA SS	MS	F Value	Pr > F
HPD	3	94.1913	31.3971	7.04	**0.0031**
NT	1	0.7004	0.7004	0.16	0.6972
HPD X NT	3	3.2513	1.0838	0.24	0.8652
HPD X NT X S/HA	16	71.4067	4.5000		
Total	23	169.5496			

Post-hoc analysis indicated that the Bilsom® Impact™ had a significantly higher masked threshold value (90.7 dBA) than did the Peltor H7 (86.1 dBA). On the other hand, the Peltor H7 device had significantly lower masked threshold value compared to both amplitude sensitive devices, i.e., the Bilsom® Impact™ (90.7 dBA) and the Peltor TacticalPro™ (90.0 dBA) devices. These results are shown in Figure 47. These results imply that in the 95 dBA noise level , non-normal hearers could hear the backup alarm at a lower masked threshold value, hence better signal detection, while wearing the Peltor H7™ passive device than with either amplitude sensitive devices (Bilsom® Impact™ and Peltor TacticalPro™).

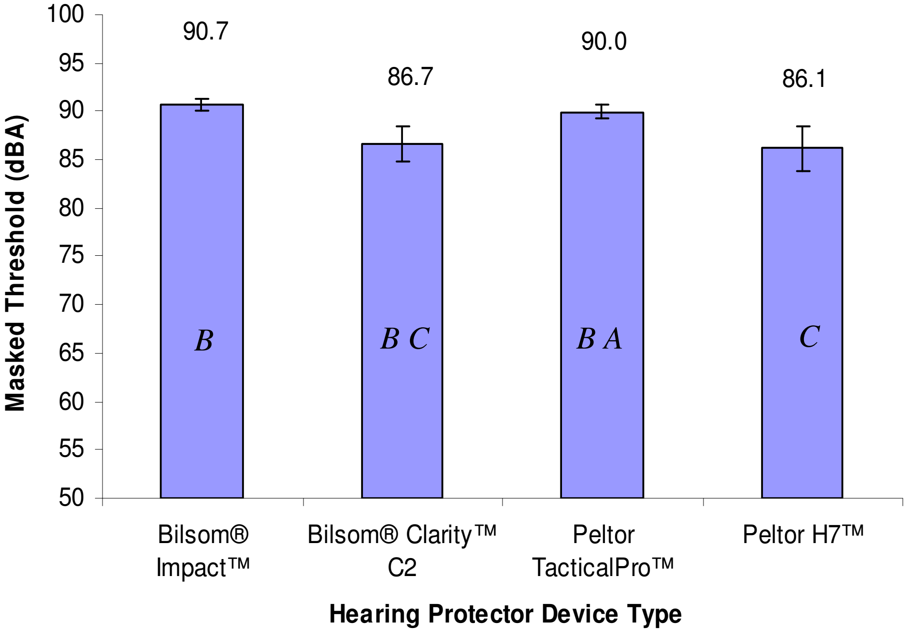

Figure 47. Effect of hearing protection device type on masked threshold for non-normal hearers at 95 dBA with 95% confidence interval. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

The most intense noise level, 105 dBA, did not result in differences of HPD on masked thresholds across all devices, i.e., Bilsom® Impact™ (98.0 dBA), Bilsom® Clarity™ C2(95.8 dBA), Peltor TacticalPro™ (98.2 dBA) and the Peltor H7™ (97.6 dBA) device (see Figure 46).

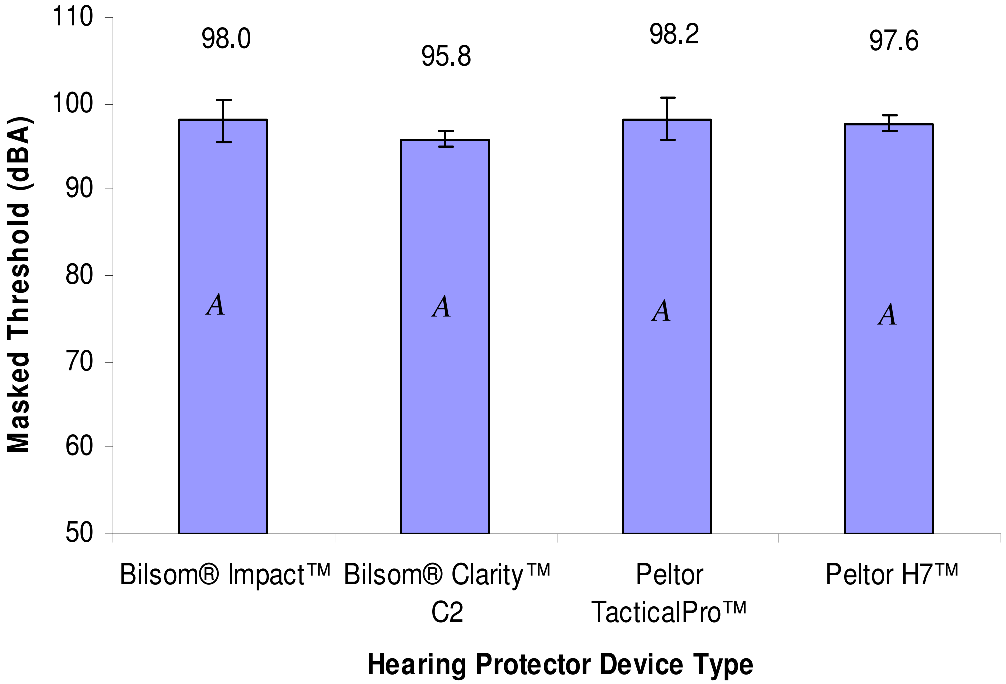

Figure 48. Effect of hearing protection device type on masked threshold for non-normal hearers at 105 dBA with 95% confidence interval. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.

Comfort and Detectability Ratings

Data obtained from the Osgood semantic differential scale (Appendix B) was used to elicit and quantify a hearing protection device wearer's subjective feeling of comfort. As explained earlier, each rating consisted of a seven point bipolar scale with an adjective at both ends. Descriptors at one end connoted an opposite subjective perception to those at the other end. Also, the descriptors on the rating scale did not have a particular directional orientation (left to right) with respect to the first scale ("Uncomfortable/Comfortable" scale), which was considered the essential scale to the participant's perception of the HPD comfort. This was done as a way to reduce the 'halo' effect on participants. If choices were based on halo effect, participants may have rated the scale consistently with one persistent impression instead of marking the scale based on independent judgment.

Ratings Analysis. The first step of data reduction for the Osgood semantic differential scale involved altering the direction on some of the scales (i.e., 7 to 1, 6 to 2, etc.) such that all scales had the same polarity with the Uncomfortable/Comfortable scale. The Uncomfortable/Comfortable scale was used as an anchor, since the overall scale was aimed at evaluating the comfort levels of each HPD. The correlation of each scale was then determined against the Uncomfortable/Comfortable scale because terms with a higher correlation with the Uncomfortable/Comfortable scale would possibly bring out feelings influencing a participant's perception of the HPD's comfort. The Pearson correlation coefficients (R) statistics were used for the rating analysis and are validated from other similar analysis such as the one done by Casali and Park, 1991. The Pearson correlation coefficients (R) are presented in Table 10.

Table 10. Pearson Correlation Coefficients (R) for each Bipolar Comfort Rating Scale with the Uncomfortable-Comfortable Scale

HPD Scale Descriptors	R
Uncomfortable/Comfortable	1.00
Painless/Painful	**0.65**
No uncomfortable pressure/Uncomfortable pressure	**0.62**
Intolerable/Tolerable	**0.70**
Tight/Loose	-0.03
Not Bothersome/Bothersome	**0.71**
Heavy/Light	**0.60**
Cumbersome/Not cumbersome	0.34
Soft/Hard	**0.56**
Cold/Hot	0.19
Smooth/Rough	**0.68**
Feeling of complete Isolation/No feeling of complete Isolation	0.20

Scales with statistical significant correlation |R|>0.045 are shown in bold and were used to develop the Comfort Index (CI), including the Uncomfortable/Comfortable scale. These indices are defined as the linear sum of all 12 items on the scales that had a significant correlation with the Uncomfortable/Comfortable scale (Casali and Park, 1991). Table 11 summarizes the mean and standard deviation values for each HPD. The minimum possible CI score was zero and the maximum possible CI score was 56 (higher scores relate to greater comfort). A non-parametric Kruskal-Wallis Test was then performed on the CI data. This test indicated no significant difference ($p \geq 0.05$) between the four devices. This result suggests that participants did not rate any HPD as more comfortable than any other HPD in the experiment. Nevertheless, it must be taken into account that participants completed the comfort rating scale based only on short experience under laboratory conditions, and that notions could change with extended use, and while on the job.

Table 11. Comfort Index means (and standard deviations) for the hearing protection devices.

Bilsom® Impact™	Bilsom® Clarity™ C2	Peltor TacticalPro™	Peltor H7™
32.7	37.7	34.5	34.7
(9.8)	(10.1)	(6.9)	(11.2)

At the end of each experimental session, participants ranked the devices from 1 to 4 (easiest to hardest) based on their perceived ability to detect the backup alarm using a semantic differential detectability scale (shown in Appendix A). The mean and standard deviation values from the questionnaire are tabulated in Table 12. The minimum possible score was zero and the maximum possible score was 7 (higher scores relate to greater difficulty in detecting the alarm). Again, a non-parametric Kruskal-Wallis Test was performed on the data, which also showed no significant differences ($p \leq 0.05$) between the four devices with respect to the participants' perceived ability to detect the backup alarm. These results suggest that participants did not rate any device better than the other for signal perception.

Table 12. Detectability index means (and standard deviations) for the hearing protection devices.

Bilsom® Impact™	**Bilsom® Clarity™ C2**	**Peltor TacticalPro™**	**Peltor H7™**
4.1	3.8	3.7	3.5
(1.7)	(1.7)	(1.1)	(1.8)

CONCLUSIONS

Sound transmission HPDs were expected to have lower masked threshold values than conventional passive HPDs for both normal and non-normal hearers for noise levels below 85 dBA, and to have the same masked threshold values as conventional HPDs for noise levels above 85 dBA. However, the results showed different outcomes for both normal and non-normal hearers at most noise levels. According to the manufacturer of the Bilsom® Impact™, the device has electronic filtering abilities that protect the ear from harmful noise and amplify the sound the listener wants to hear (www.labsafety.com). The amplification limiting levels are a "safe" 82 dBA (www.labsafety.com). In correspondence with the above, the manufacturers of the Peltor TacticalPro™ (the other sound transmission device) state that their device offers active protection from dangerous noise levels, while still amplifying safe sounds such as safety alarms. The built-in inhibitor in the device restrains the sound amplification levels at a safe 82 dBA (Peltor TacticalPro™, user manual). However, the results of this experiment do not support those claims for either sound transmission HPD, as detailed in the data analysis part.

Normal Hearers and Non-Normal Hearers combined . The passive devices showed an advantage on masked threshold detectability than the sound transmission devices for all participants across the 75 dBA, 85 dBA and 95 dBA noise levels, and no differences on the 105 dBA noise levels. The results for the 75 dBA, 85 dBA and 95 dBA noise levels may be due to the fact that the sound transmission devices amplified *both the backup alarm and the masking noise,* hence making it difficult for the listener to perceive the backup alarm in the all three noise levels. Also, the Bilsom® Impact™ had higher masked threshold than the Peltor TacticalPro™ in the 75 dBA and 85 dBA noise levels. This may be due to other aspects of the device such as bulkiness and shape of cup.

Normal Hearers. Based on results obtained from this study, the sound transmission devices offered no advantage over the passive devices in terms of masked threshold detectability for individuals with normal hearing across all noise levels. Particularly for the noise level at 75 dBA, both passive devices (Bilsom® Clarity™ C2 and Peltor H7™) had significantly lower masked threshold values than the Bilsom ® Impact ™ sound transmission device. This is inconsistent with the first hypothesis (H_1), which anticipated that the sound transmission devices would have a lower masked threshold value than the passive devices. A possible explanation for this finding is that the sound transmission devices amplified *both the backup alarm and the masking noise,* hence making it difficult for the listener to perceive the backup alarm in the lowest noise level. The high masked threshold value for the Bilsom® Impact™ device could possibly due to other aspects such as bulkiness and shape of cup. A number of the participants verbally complained that while wearing this device, with the electronics turned on, it was difficult for them to distinguish the backup alarm from the background noise, suggesting that both the unwanted harmful background noise and the essential backup alarm were amplified. These results suggest that, contrary to the manufacturer's indications, both devices were not able to distinguish 'unwanted' noise from 'the sound the listener wants to hear;' in this case, the backup alarm. Instead, the devices amplified all sounds, regardless of whether or not they were safety-critical. Another participant complained of the loudness of the Peltor TacticalPro™ device when the electronics were turned on without any Masking noise, and as causing pain in her ears each time the background was presented to her while she was wearing the device. This anecdote suggests that the Peltor TacticalPro™ device was presenting internal electrical or other sounds to the listener in the absence of noise, or perhaps creating/amplifying artifacts of external noise.

For the rest of the noise levels (i.e., 85 dBA, 95 dBA and 105 dBA), the sound transmission devices did not show any advantages in masked threshold over the passive devices for normal hearers. These results support the second hypothesis (H_2), which anticipated that both device types should have a same masked threshold values for noise levels above 85 dBA. This might be an indication that as advertised the sound transmission devices, in noise levels above about 82 dBA, did indeed shut off as stated earlier, inhibiting the amplification ability, and essentially acting as passive devices.

Non-Normal Hearers. Results obtained from this study indicate that the sound transmission devices have a disadvantage when compared to their counterpart passive devices on backup alarm masked threshold in 75, 85 and 95 dBA noise levels for hearing impaired users. This, again, might be due to the fact that the sound transmission devices amplified both the signal and the background noise, therefore making it difficult to perceive the backup alarm. In 105 dBA noise, the sound transmission device did not differ from the passive devices in backup alarm masked threshold. This again might be an indication that in noise levels above about 82 dBA (although not evident in the 85 and 95 dBA), the internal circuitry of the sound transmission devices indeed shut off, allowing the devices to only act as passive HPDs.

Overall. Based on the results of this study, in an overall sense sound transmission devices offer no advantages over passive devices in signal detection. On average, across all noise conditions, the passive devices showed an advantage of about 3 dB over the sound transmission devices in backup alarm masked theshold. This can probably be attributed to the fact that the latter devices amplified both the noise and the signal, therefore making it difficult for the listener to detect the signal. According to the manufacturers of Bilsom® Impact™ and Peltor TacticalPro™ the actual limiting level of amplification for these sound transmission devices is 82 dBA (Bilsom® Impact™ website), however these levels (82 dBA) were never reached as documented by the pilot study results shown earlier in Figure 25a and Figure 26a. At the lowest noise levels measured in the pilot study (75 dBA), the maximum under-ear cup amplification levels recorded were a low 69 dB for the Bilsom® Impact™ and 66 dBA for the Peltor TacticalPro™. This clearly indicates that sound transmission devices were not able to reach the actual limiting level of amplification (82 dBA) that the manufacturers claim. This shows that in a noisy condition (such as 75 dBA) the sound transmission device might not perform to its full expectation, hence making it difficulty for the user to perceive the backup alarm when wearing the devices. With these results,manufacturers may need to do further Laboritory experiments on the technology of sound transmission devices to verify two essential parts of the operational of sound transmission technology.

1. Verify that these devices only amplify the essential sounds (in this case, the backup alarm) that need to be heard, and not amplify both the essential and background (harmful) noise.
2. Verify the actual limiting level of amplification for the devices to be 82 dBA and not the low 69 dBA and 66 dBA for the Bilsom® Impact™ and the Peltor TacticalPro™ respectively, obtained in our pilot studies.

These findings also help to dispel the initial concerns of a similar study (Casali & Wright,1995) which questioned whether that the lack of differences in masked threshold between passive and sound transmission device may have been due to the Hughson-Weslake 5 dB procedure used in the experiments; this study had a 1dB resolution, and also had similar results with Casali &

Wright's study, which eliminates measurement resolution criterion as the cause of lack of significant differences between passive and sound transmission devices.

An important factor in determining the attenuation of a HPD is comfort (Park and Casali, 1991). An uncomfortable HPD may result in workers removing the device during work, thus resulting in significant reduction in attenuation (Casali, Lam, and Epps, 1987; Park and Casali, 1991). The study did not show any statistical differences of sound transmission devices over the passive devices, thus it could not be concluded whether one type of HPD was more comfortable than the other).

LIMITATIONS

It is important to discuss the limitations of the research and how they can influence the interpretation of the results. Most notable is the fact that out of all of the resources and numerous potential participants that were contacted through fliers, emails, word of mouth, and other hearing clinics, only three participants with hearing loss meeting the non-hearing criteria were recruited and participated in the study. This had an effect of reducing the overall power (1- β) of the ANOVA, thus enhancing the potential of making a type II error (β – failing to reject the null hypothesis when, in fact, it is false).

FUTURE STUDIES

One main factor that this study did not address is the issue of attention. This experiment and many other laboratory-based experiments that deal with masked threshold issues make the recordings while the subject is attentively listening to the signal to be heard. While this might provide one with the true threshold values, it does not represent a true work environment. It is important to note that workers in a typical work environment are not idly sitting or waiting to hear a signal they are supposed to be aware of; instead, they are busy working and doing other tasks.

Other devices with similar technology such as ANR devices (that rely upon the principle of *destructive interference* to cancel the noise) may also be tested in the construction environment so as to help workers hear signals and protect their hearing.

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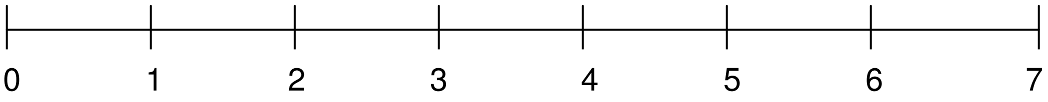
APPENDIX A

Subject: ______________________________Date: ________________HPD:__________

RATE THE LEVEL OF DIFFICULTY IN DETECTING THE BACKUP ALARM SIGNAL UNDER THE HEADSET YOU ARE WEARING



Extremely easy to detect	Extremely difficult to detect

APPENDIX B

Subject: ______________________________Date: ________________HPD:__________

HOW DOES THE HEARING PROTECTOR FEEL NOW?

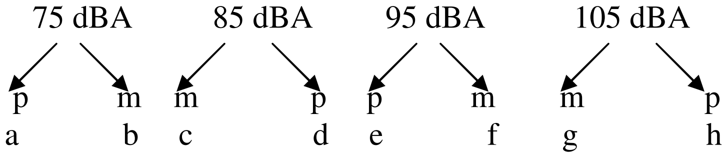
Uncomfortable	0	1	2	3	4	5	6	7	**Comfortable**
Painless	0	1	2	3	4	5	6	7	**Painful**
No Uncomfortable pressure	0	1	2	3	4	5	6	7	**Uncomfortable pressure**
Intolerable	0	1	2	3	4	5	6	7	**Tolerable**
Tight	0	1	2	3	4	5	6	7	**Loose**
Not Bothersome	0	1	2	3	4	5	6	7	**Bothersome**
Heavy	0	1	2	3	4	5	6	7	**Light**
Cumbersome	0	1	2	3	4	5	6	7	**Not cumbersome**
Soft	0	1	2	3	4	5	6	7	**Hard**
Cold	0	1	2	3	4	5	6	7	**Hot**
Smooth	0	1	2	3	4	5	6	7	**Rough**
Feeling of complete isolation	0	1	2	3	4	5	6	7	**No feeling of complete isolation**

Is there a specific feature of the hearing protector that would cause you not to wear it?
Yes________ or No________ If yes, what feature or features?
____

APPENDIX C

Latin Square design

<u>Noise levels/types</u>



1. HPD 1 →g f b d c h a e
2. HPD 2 →a b g f h d e c
3. HPD 3 →b h f e g a c d
4. HPD 4 →f c d a e b g h

Where
HPD 1 = Bilsom® Impact™
HPD 2 = Bilsom® Clarity™ C2
HPD 3 = Peltor TacticalPro™
HPD 4 = Peltor H7™

<u>Subjects are assigned to conditions as follows:</u>

NORMAL HEARERS

1 1234
2. 4321
3. 2143
4. 3412
5. 2341
6. 3214
7. 1432
8. 4123

NON-NORMAL HEARERS

9 1234
10. 4321
11. 2143
12. 3412
13. 2341
14. 3214
15. 1432
16. 4123

APPENDIX D

SCREENING SESSION

1. The experimenter greets the prospective participant.
2. The prospective subject reads and signs two copies of the informed consent form (one for them, one for ASL's records).
3. The experimenter gives the prospective participant a full verbal description of the experiment and the screening procedure.
4. The experimenter asks several questions to the prospective participant about his/her auditory health (consistent with the normal ASL HPD screening procedure).
5. The experimenter performs an otoscopic examination to the prospective participant to ensure full view of the tympanum. Any obstructed view of the tympanum, by excessive earwax or other, is cause for participant dismissal. Experimenter refers participant to Schiffert Health Center for aural exam/removal procedures.
6. The experimenter will perform a pure-tone audiogram on the prospective participant while, s/he is sitting in the anechoic chamber, inclusive of the frequencies of 125 Hz to8000 Hz.
7. The prospective participant is grouped as either normal or non-normal hearer, depending on the outcomes of the pure-tone audiogram test (e.g., [normal hearers will have pure tone Hearing Abilitys in both ears at the 1/3-octave band center frequencies from 125 Hz-8 KHz that are ≤25 dBHL; *non-normal hearers* will have a pure tone Hearing Ability <u>in the better ear</u> of >/= 40 dBHL in at least one of the following frequencies: 1, 2, and 3 KHz.

APPENDIX E

THE EXPERIMENTAL SESSION

1. BEFORE PARTICIPANT ARRIVES

   a. Turn on all of the equipment, and allow warming up for at least 15 min.
   b. Calibrate the testing room.
      - Position measurement microphone stand at head center position.
      - Turn on calibrator, insert microphone.
      - Ensure L/D 2800 analyzer reads 94 dB @ 1 KHz (adjust as needed).
      - Remove microphone from calibrator.
      - Ensure that microphone and stand are at head center position.
      - Adjust noise level of Infinity loudspeakers to pre-labeled volume setting on amplifier (**ensure that all four speakers are outputting noise**).
      - Measure volume setting and adjust amplifier to desired level.
      - Turn off noise.
      - Turn on Klipsch horn backup alarm.
      - Measure/verify frequency of backup alarm to be ~1250 Hz.
   c. Verify the noise spectra for the 1994 CMI PR-500B road-milling machine by referring to measured spectrum.

2. FAMILIARIZATION (THRESHOLD TRACKING TASK)

   a. The experimenter shall verify the noise intensity of the noise (Caterpillar tractor in operation, Sound Effects Vol. 5, Track 19) which should be set at 95 dBA.
   b. The experimenter shall also verify the level of the backup alarm intensity. This should be set at the 95 dBA Masking Noise level on the knob of the amplifier controlling the backup alarm gain.
   c. Once the participant comes in, s/he is greeted and seated in the chair where the threshold monitoring task will occur.
   d. The participant will be fitted with all hearing devices one at a time to make sure that all devices fit properly. If any device does not fit properly, reject participant.
   e. The experimenter will give a verbal description of the overall experiment and the of the threshold monitoring "familiarization" task to the participant.
   f. The participants will be presented with a Peltor H-10A earmuff, which will be fitted by experimenter to ensure proper fit.
   g. The experimenter shall make sure that the participant is seated upright with front leg of the chair directly above the crossed 'x' mark on the floor, and that the participant is seated at head center position. Participant is instructed to maintain their head/chin as close to the head center position as possible, and to not move during testing.
   h. The experimenter is seated behind the workstation desk.

i. The experimenter makes sure that the backup alarm intensity is at its lowest intensity on the laptop wave volume control.
j. The experimenter plays the backup alarm (looped on windows media player).
k. The experimenter starts the wave graph on Labview software.
l. Masking noise in the form of a caterpillar tractor in operation at 95 dBA will be presented.
m. Once the Masking noise starts, the participant should silently count to five, and on the fifth count, the participant should begin the tracking task.
n. Participant will track a backup alarm signal using a wheel scroll on a mouse.
o. Participants given about 30 seconds to complete this task.
p. The experimenter shall actuate the pause button on windows media player to stop the backup alarm signal
q. The experimenter actuates the mute button on the amplifier to terminate the masking noise.
r. The experimenter will save the recorded tracking graph on the computer, and label it according to participant and trial.
s. The participant shall discontinue the tracking task
t. Steps h through t are repeated 4 times, for a total of five tracking trials.

3. DATA COLLECTION SESSION

a. The experimenter sets the specific Masking noise level/type for that session before the participant enters the room (i.e., Step 1 above).
b. The experimenter shall set the specific level of the backup alarm intensity using volume knob on the amplifier controlling the backup alarm intensity.
c. Once the participant comes in, s/he is greeted and seated in the chair where the threshold monitoring task will occur
d. The experimenter will give a verbal description and procedure of the experiment. The participant is presented with the following script to read,
    1. *The purpose of the experiment is to investigate the detectability of a backup alarm signal while wearing the earmuffs in different kinds and intensities of noise.*
    2. *Once the earmuff is fit on your head, please do not touch or take off the device until you are told to do so by the experimenter.*
    3. *Please sit at the desk and position your head/chin such that it is within one inch of the head reference, and do not move your head at any time during the testing.*
    4. *Once the Masking noise is presented, please silently count to five and then start the auditory tracking task.*
    5. *You should use the mouse scroll wheel in front of you to increase and decrease the backup alarm noise. First, roll the scroll wheel forward to turn the backup alarm volume up to a level where you are completely sure that you hear the alarm. Then roll the scroll wheel backwards, until you no longer can hear the backup alarm. Then turn the backup alarm volume up again, this*

time to a level that you can just barely hear the alarm, but still sure you can hear the alarm. Then turn the volume down again to a level where you can no longer hear the alarm. Continue this process of increasing the volume of the alarm until you can hear it, and then decreasing the volume until you cannot hear it, over and over, until the noise stops.

e. The experimenter will fit the participant with the hearing device.
f. Once the device is fitted, the experimenter shall raise the lower part of the cup to make sure that the participant's earlobes are completely within the earcup.

   BILSOM IMPACT ™

   - If the hearing device is a Bilsom Impact ™, the experimenter should make sure that the amplification knob is fully turned on to its highest level (i.e., full right turn).

   PELTOR TACTICAL PRO™

   - If the device is a Peltor Tactical Pro™, the experimenter shall press and hold the "on" button on the device for about 3 seconds. The participant is requested to listen for an audible 'beep,' indicating that the device is turned on.
   - The experimenter shall verify with the participant to make sure that the device is indeed on.
   - The experimenter shall press and hold the "+" button for 5 seconds to maximize the gain on the device.

g. The experimenter shall make sure that the participant is seated straight with front leg of the chair directly above the crossed 'x' mark on the floor, and that the participant's head is centered with the head reference and is about 1 inch from it.
h. The experimenter is seated behind the workstation desk.
i. The experimenter makes sure that the backup alarm intensity is at its lowest intensity on the laptop wave volume control.
j. The experimenter checks both of the amplifier gain settings controlling the Masking noise and backup alarm signal on the amplifiers to make sure they are at the appropriate levels.
k. The experimenter initiates the backup alarm on windows media player (looped 'on').
l. The experimenter starts the wave graph on Labview.
m. The experimenter presents the specific Masking noise for the condition being tested for (i.e., either pink or milling machine noise).
n. Once the Masking noise starts, the participant should silently count to five, and after the fifth count, the participant should begin the tracking task.
o. Participant will perform the tracking task using a wheel scroll on the mouse located on the desk in front of them.
p. Participants given 30 seconds to complete this task.
q. The experimenter shall actuate the pause button on windows media player to stop the backup alarm signal.
r. The experimenter actuates the mute button on the amplifier to terminate the Masking noise.

s. The experimenter will save the recorded tracking graph on the computer, and label it according to participant and trial.
t. The participant shall discontinue the tracking task.
u. Steps g through t are repeated 4 more times.
v. Upon completion of the Masking noise level conditions, the electronics are turned off (if the headset is a sound transmission device).
w. The participant is asked to exit the room and sit on the chair located outside of the room. The following script will be read the participant before s/he leaves the room,*" Please do not remove or adjust the hearing protector during this break. It is important that the fit of the hearing protector be consistent across all trails conducted during a single session."* In the meantime, the experimenter sets and verifies the next Masking noise level/type and the next backup alarm level (based on participant/condition ordering on page 1).
x. Upon completion of next trial setup, the participant is called back in the room and seated in the chair.
y. Steps g through v are repeated.
z. Upon completion of all of the Masking noise level/intensity conditions of the specific headset, the participant is given the semantic differential scale to rate the device's ability to detect the backup alarm.
aa. Upon completion of the aforementioned scale, the participant is then given a comfort rating scale and is asked to rate the subjective comfort of the hearing device.
bb. Upon completion of both scales, the headset will be removed from the participant's head by the experimenter.
cc. The experimenter shall fit the participant with the next headset (again, based on the participant/condition ordering on page 1.)
dd. Steps d through bb are repeated.

<u>Only on the last day of the experimental sessions</u>

ee. On the last experimental session, after the participant has completed all of the experimental conditions, s/he is presented with all of the headsets (placed on a table, side-by-side), and is once again given the semantic differential scale to rate the devices' ability to detect signals.