THE DETECTION OF WARNING SIGNALS WHILE WEARING ACTIVE NOISE REDUCTION AND PASSIVE HEARING PROTECTION DEVICES

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
in
Industrial and Systems Engineering
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July 15, 1999
Blacksburg, Virginia

Keywords: Audition; Hearing Protectors; Hearing Protection Devices, Passive Hearing Protection Devices, Active Hearing Protection Devices, Active Noise Reduction, Active Noise Cancellation

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(ABSTRACT)

The research described herein was undertaken to determine how masked thresholds changed when individuals wore an *active noise reduction* (ANR) hearing protection device (HPD), a passive HPD, or no HPD. An ANR earmuff, a passive earmuff, and a user-molded foam earplug were tested in two types of noises (pink and red) at two different noise levels (85 dBA and 100 dBA). The signal used was an industry-standard backup alarm. The experimental design was completely within-subjects. An ascending method of limits was used to obtain 15-20 correct positive responses, which were then averaged to obtain the masked thresholds for each treatment condition. A visual probability monitoring task was incorporated in the experimental design to provide a loading task for the participants. In addition to masked thresholds, comfort and mental workload were assessed. Finally, participants were asked to rank each of the three HPDs with respect to their perceived ability to facilitate hearing the signal in noise.

Results indicated that in 85 dBA noise, masked thresholds were lower when hearing protection devices were worn, compared to the unoccluded condition. Additionally, the results indicated that the ANR device provided a significant advantage (lower masked thresholds) over the passive earmuff in the low-frequency biased red noise (across both noise levels) and the 100 dBA noise level (across both noise spectra). However, the ANR earmuff exhibited no significant advantage over the user-molded foam earplug in any of the conditions. Rather, the user-molded foam earplug produced significantly lower masked thresholds at 100 dBA. The results also indicated that there was no difference between the three devices in their perceived ability to facilitate detection of the signal. There was also not a significant difference in comfort ratings between the three HPDs, although there were several complaints about the comfort of the ANR earmuff during the experiment.

ACKNOWLEDGEMENTS

I would like to express my gratitude to those individuals who made this research possible. First, special thanks to Dr. John G. Casali, the committee chairman, for his advice and encouragement through the years. Considerable thanks are also extended to Dr. Gary S. Robinson for his knowledgeable advice, invaluable guidance, and patience throughout the research effort. Thanks are also due to Dr. Robert J. Beaton and Dr. Ned E. Carter for their encouragement and interest in this research project. Special thanks to Dr. Suzie E. Lee for her comments, suggestions, and encouragement during the research effort.

Thanks are due to Dan Gauger of the BOSE Corporation for suggesting the research problem and for providing both funding for the study and donating equipment to the laboratory.

I would like to extend thanks to Mr. Will Vest, Mr. Jeff Snyder, and Mr. Randy Waldron of the Industrial and Systems Engineering Department for their services in helping to prepare the equipment and instrumentation for the experiment. I would like also thank Mr. Mark Crabtree of Logicon Technical Services, Inc. for providing the probability monitoring computer program used in the experiment.

I am also truly thankful to Dean Bevlee A. Watford for the encouragement, support, and mentoring she has provided throughout the years. Finally, special thanks are extended to my parents, Prentice and Ruby Christian, and my husband, Airren Dabney, without their love, understanding, support, encouragement, and prayers this achievement would not have been possible.

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CHAPTER 1: INTRODUCTION

Over 9 million workers are exposed daily to occupational noise exceeding 85 dBA (EPA, 1981). In addition to causing noise-induced hearing loss, excessively high noise levels can degrade communications, safety, and job performance (Suter, 1986). The most common method used to combat the adverse effects of noise is the use of hearing protection devices (HPDs), implemented as part of a hearing conservation program.

Worker compliance in hearing conservation programs often is low. The attitude of many workers is that the use of hearing protection impairs auditory detection (Wilkins and Martin, 1987). Figure 1 depicts results from a survey of 80 industrial workers conducted by Karmy and Coles (cited in Wilkins and Martin 1987), in which they assessed workers' attitudes about HPD usage and their ability to hear warning signals. In the diagram, "1" represents the number of workers who reported no warning sounds present at their workplace; "2" represents the number of workers who reported that warning sounds were present at their place of work. Of those who reported warning sounds in their workplace, "A" represents the portion of respondents who reported that it was easier to hear them while wearing HPDs; "B" represents those who reported that their ability to hear them was unchanged when wearing hearing protectors; and "C" represents those who reported that is was more difficult to hear the warning signal while wearing hearing protectors. As seen in Figure 1, of those respondents who indicated that warning sounds were prevalent at their place of work, most reported that they believed wearing HPDs made warning signals more difficult to hear.

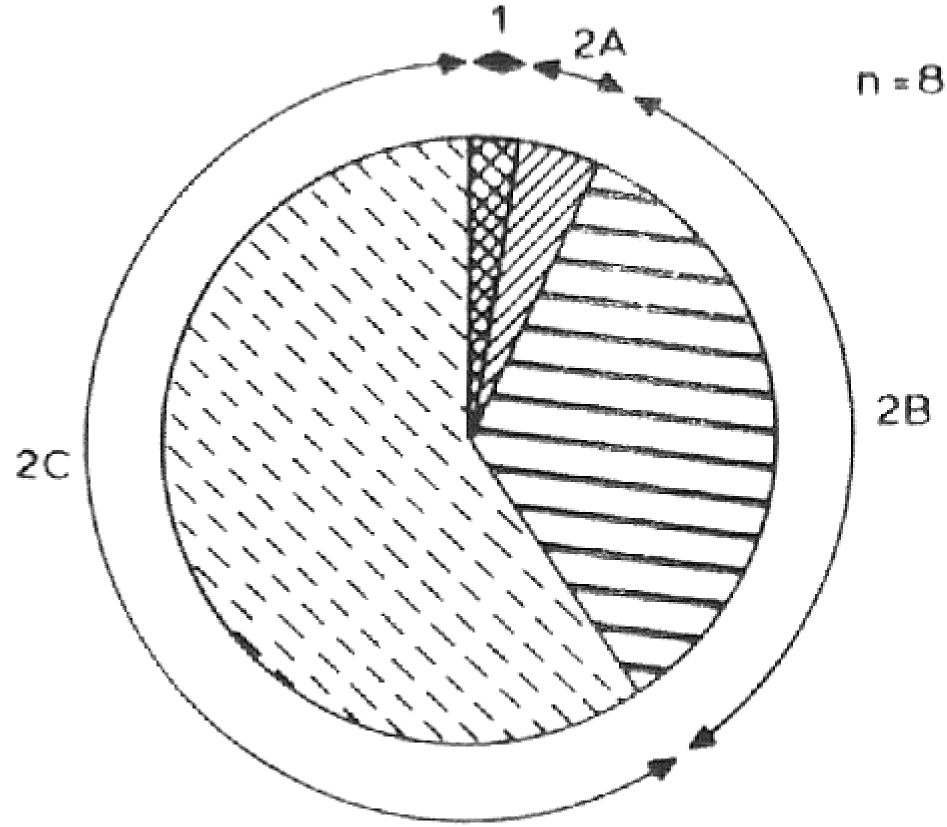


Figure 1. *Results from a survey of worker attitudes about whether the use of hearing protection devices impairs their ability to hearing warning signals, conducted by Karmy and Cole in 1977.* (cited in Wilkins and Martin, 1987)

Research has not supported this belief, at least for individuals with normal hearing and when background noise exceeds about 85 dBA (Forshaw, 1977; Wilkins and Martin, 1977). The reason for this is that at high noise levels, the ear distorts the signal being transmitted to the brain making it difficult, if not impossible, for the listener to distinguish a desirable signal from the background noise. Conventional HPDs attenuate overall noise levels reaching the ear, reducing the distortion and thus making it easier for the listener to distinguish the desired signal from the backgrounds noise, even though their levels relative to one another remain unchanged (Suter, 1989). Another, perhaps more effective approach might be to selectively reduce the background noise more than the desired signal. *Active noise reduction* (ANR) technology has the potential to do just that. The study described herein compares the detectability of signals in noise while wearing active and conventional passive HPDs to determine if ANR lives up to its potential.

CHAPTER 2: MASKING

When an auditory signal is presented in background noise, as is the case in industrial settings, it must be presented at a higher *sound pressure level* (SPL) than would be necessary in quiet for it to be heard. This is due to *masking*, which is defined as the tendency for the threshold of a signal to be raised in the presence of background noise. This elevated threshold is termed the *masked threshold*. In assessing the detectability of a signal in any real-world scenario, it is necessary to consider masking. The basic principles of masking are discussed briefly below.

Masking by Pure Tones

Masking by pure tones occurs when a tonal signal is masked by another tonal noise (the masking tone). In this scenario, masking is greatest at frequencies near the masking tone. Furthermore, masking is greater at frequencies above that of the masking tone than at frequencies below that of the masking tone. This phenomenon is referred to as the upward spread of masking and becomes more pronounced as the sound pressure level of the masking tone increases. At the frequency of the masking tone (and its higher harmonics) a phenomenon referred to as beats occurs. Beats are periodic variations in amplitude that result from the superposition of two simple harmonic waveforms with different frequencies (ANSI, 1973). In this case, they are created when the frequency of the masked tone and masking tone are very close, and make it easier for a listener to detect the presence of the desired tonal signal (Deatherage, 1972).

Masking by Narrow Bands of Noise

Egan and Hake (1950) performed a classic study on masking of tonal signals by narrow bands of noise, concluding that narrow bands of noise were more efficient maskers than were pure tones. Figure 2. illustrates the masking of a 410 Hz tone by a 90 Hz wide band of noise centered at 410 Hz presented at three sound pressure levels (40, 60, and 80 dB). From this graph, it is apparent that the beat phenomenon and notches that were evident with pure tones are not present, but that the upward spread of masking still occurs at the higher sound pressure levels.

Masking by Broadband Noise

Hawkins and Stevens (1950) investigated the masking of pure tones by broadband white noise (flat by frequency - having uniform spectral power). They determined masked thresholds for pure-tone signals at 16 frequencies from 100 to 9000 Hz for eight levels of masking noise. Their results indicated that masking produced by a broadband noise is proportional to the level of the noise (i.e. increasing the level of the masking noise by 10 dB results in a 10 dB increase in the masked threshold) as evidenced by the equal spacing of the contours shown in Figure 3. (The dotted lines that occur at frequencies above 6000 Hz represent nonlinearities in the experimental apparatus.)

Critical band theory (Fletcher, 1940), allows the masked threshold of a pure-tone signal masked by white noise or any reasonably flat broadband noise to be calculated. The theory is based on the assumption that the ear behaves like a narrow-band filter with a bandwidth proportional to the frequency of the tone being masked. Noise outside this band does not contribute to the masking of the tone (Deatherage, 1972). Hence, the masked threshold of a

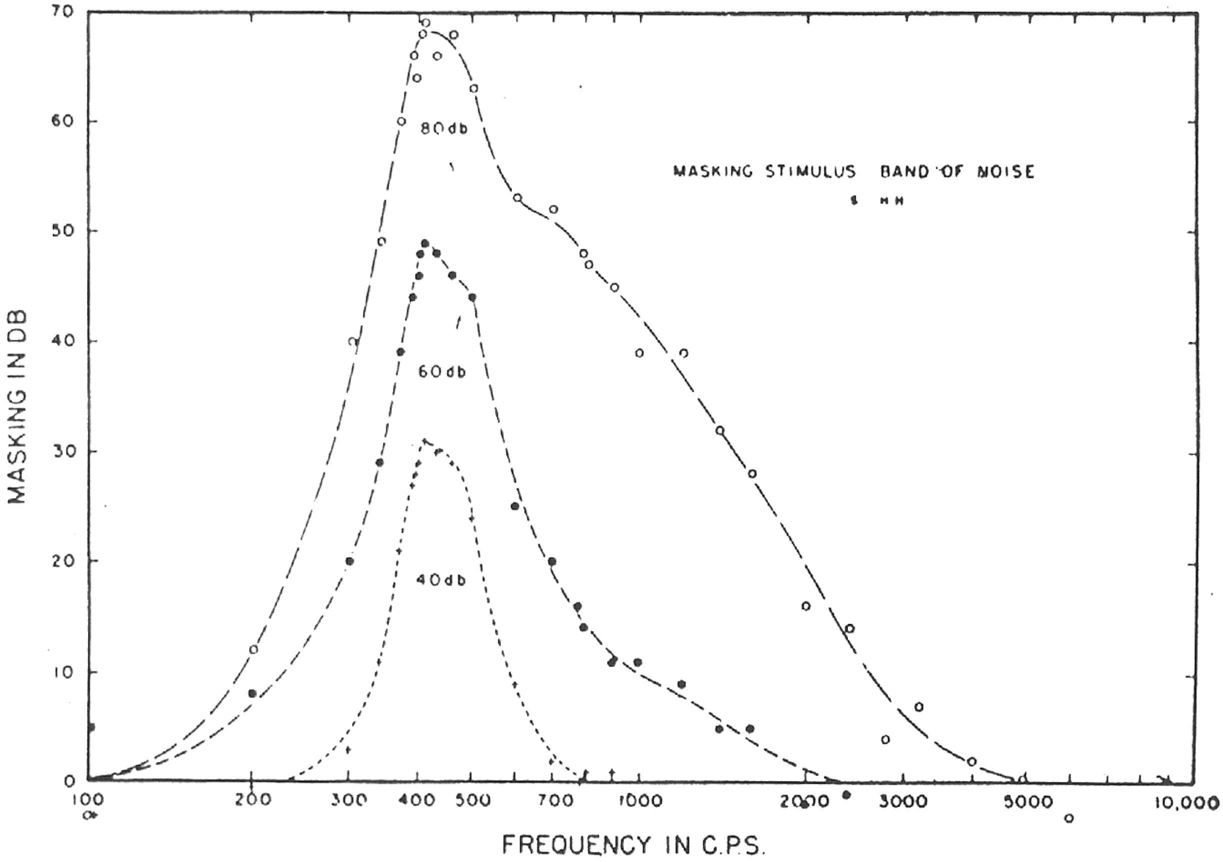


Figure 2. *Plot of masking vs. frequency of the masked tone for masking of pure tones by narrow bands of noise*. (from Egan and Hake, 1950)

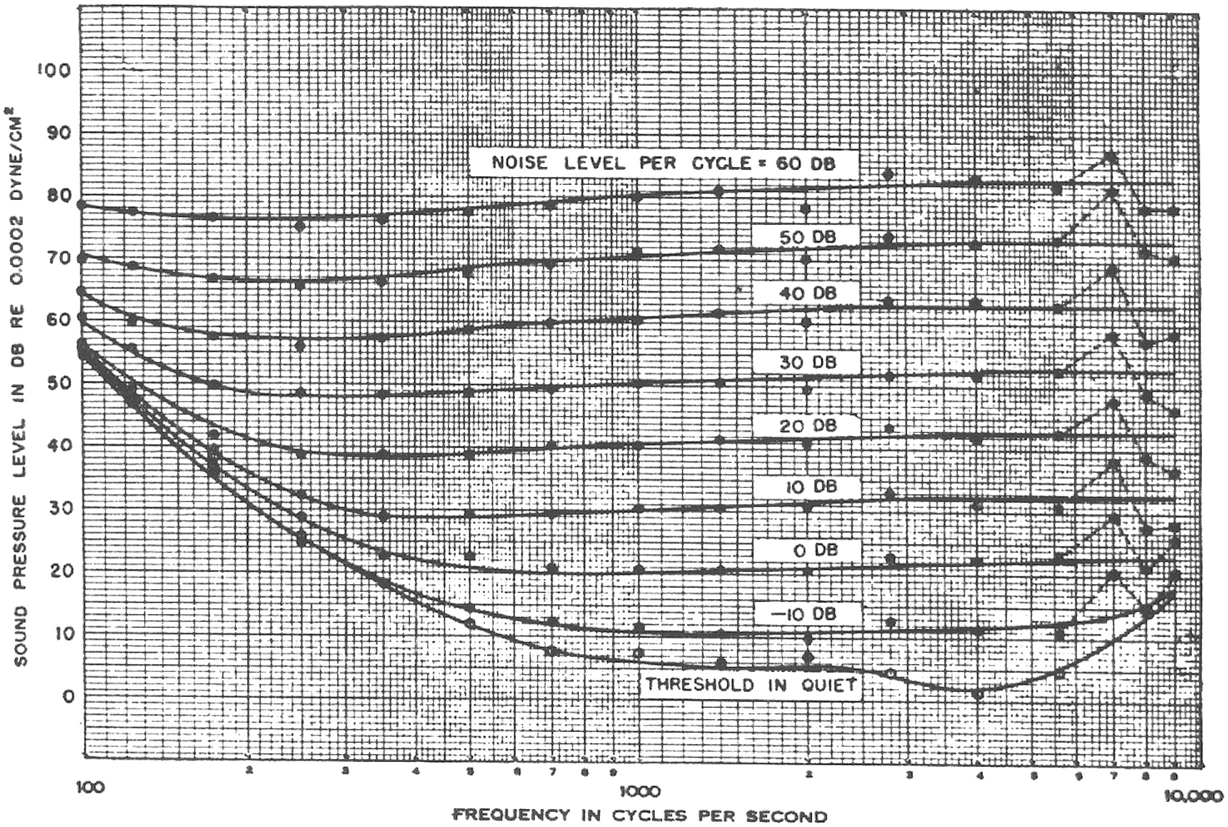


Figure 3. *Masked threshold of pure tones when masked by broadband noise of uniform spectrum.* (from Hawkins and Stevens, 1950)

pure tone can be predicted if the spectrum level of the masking noise (assuming it is reasonably flat near the tone in question) and the frequency of the tone are known. The equation for predicting the masked threshold at a frequency *f* follows:

$$\text{Masking Threshold} = L_{\text{spectrum}} + 10\log_{10}(\text{BW})$$

Where: L_{spectrum} is the spectrum level (level per unit cycle, e.g., the level that would be measured using a filter 1 Hz wide – ANSI, 1973) of the broadband masking noise. BW is the critical bandwidth centered around the tone and can be calculated as:

$$\text{BW} = 0.15 * f$$

CHAPTER 3: HEARING PROTECTION DEVICES

As stated earlier, over 9 million workers are exposed daily to occupational noise exceeding 85 dBA (EPA, 1981). The Occupational Safety and Health Administration (OSHA) requires that when the 8-hour time weighted average (TWA) reaches 85 dBA, a hearing conservation program must be implemented. When the TWA exceeds 90 dBA, the employer must reduce the noise exposure level, if feasible, or use personal hearing protection. Noise exposure level reduction can be executed by three different methods: engineering controls, administrative controls, and the use of hearing protection devices.

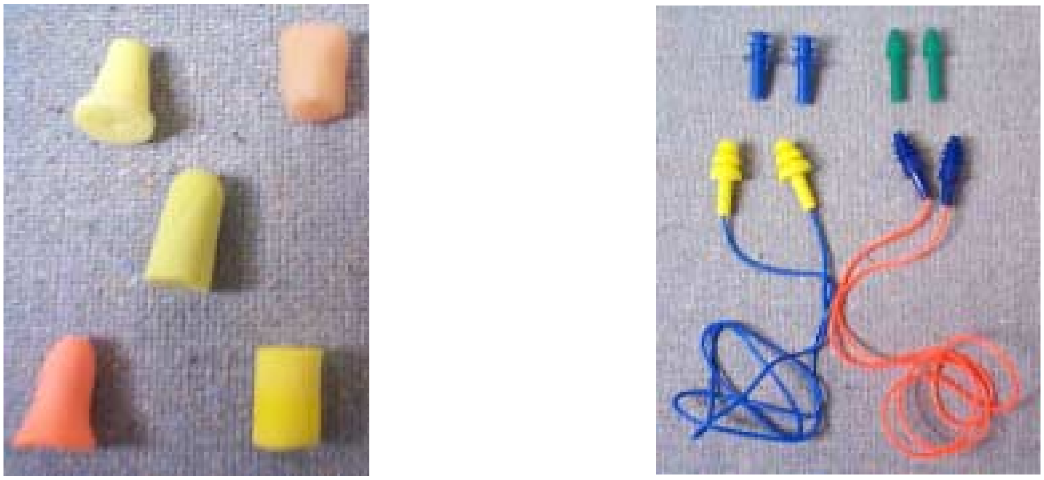
The preferred way to reduce noise exposure is through engineering controls. Engineering controls involve the elimination of noise at its source or in its transmission path and include such measures as adding sound absorbing material to ceilings and walls, isolating vibrating machinery, using sound insulating joints, replacing noisy machines and processes with quieter ones, and constructing barriers to separate working areas from noise machinery (Anton, 1989). Although considered the best solution to excessive noise exposure, engineering controls are the most costly alternative and may be infeasible.

Administrative controls reduce employees' noise exposure by limiting their time in the noisy environments. This often can be accomplished through job rotation or job sharing, where workers rotate between noisy and quieter jobs. Another way of implementing administrative controls is to divide the noisy job among two or more employees so that the job is completed in less time thus reducing the time workers are exposed. These methods usually are not popular or successful because they hinder productivity and because unions often object to the practice. Most importantly, they do not eliminate the problem; instead of having one or two employees with severe hearing loss, there are many employees with slight to moderate hearing loss (Suter, 1986).

While hearing protectors are intended to be used only in cases when engineering or administrative controls are infeasible or ineffective, they are perhaps the most widely implemented solution to combat the negative effects of noise exposure in industry. The reason is that they are economical and easy to implement. The three most commonly used types of HPDs are earplugs (pre-molded, user-molded, and custom-molded), earmuffs, and ear canal caps, Figure 4. Such devices reduce the noise level at the ear by physically blocking the air

Ear Caps

Earmuffs



User-Molded Earplugs

Pre-Molded Earplugs

Figure 4. *Typical examples of four types of hearing protectors.*

conduction pathway. However, the attenuation characteristics of the different HPD designs differ considerably. Figure 5 illustrates the attenuation characteristics of four commonly used HPDs.

Earplugs

Earplugs are worn by being inserted into the ear canal. They have an advantage over earmuffs and canal caps in that they attenuate low-frequency noise more effectively and do not affect the user's ability to wear eyeglasses, earrings, hardhats, goggles, respirators, or other items of safety equipment. While earplugs are often more comfortable in hot and humid environments than earmuffs, they are not suited for dirty environments. In addition, monitoring earplugs for deterioration and cleanliness is imperative to preventing ear infection or other problems with the ear. Proper insertion is also critical to obtaining adequate attenuation (Casali and Epps, 1986); however, a good fit is sometimes difficult or impossible to achieve due to variation in the size and shape of the wearer's ear canal.

There are three general classes of earplugs: pre-molded, user-molded, and custom- molded, and each type has its associated advantages and disadvantages. Pre-molded earplugs are made from soft rubber, vinyl, or silicone compounds, usually have one or more flanges to aid in creating an effective seal, and are available in a variety of sizes. The main disadvantage of this type of earplug is that it has to be reinserted periodically to maintain a tight seal due to physical activity on the part of the wearer (Park and Casali, 1991). For example, jaw movement while talking or eating can cause the earplug to back out of the ear canal.

User-molded earplugs are made from spun fiberglass, waxed cotton, or vinyl or polyurethane foam. Since user-molded earplugs attempt to mold themselves into the shape of the ear canal in which the are inserted, variation in the size and shape of the ear canal is less problematic than with pre-molded earplugs. Unlike pre-molded and custom-molded earplugs, however, user-molded earplugs cannot be cleaned when they are dirty and have to be replaced at greater frequency. However, they are often much less expensive than other types of HPDs. The attenuation characteristics of user-molded earplugs and pre-molded earplugs are similar, with user-molded earplugs achieving higher attenuation at lower frequencies.

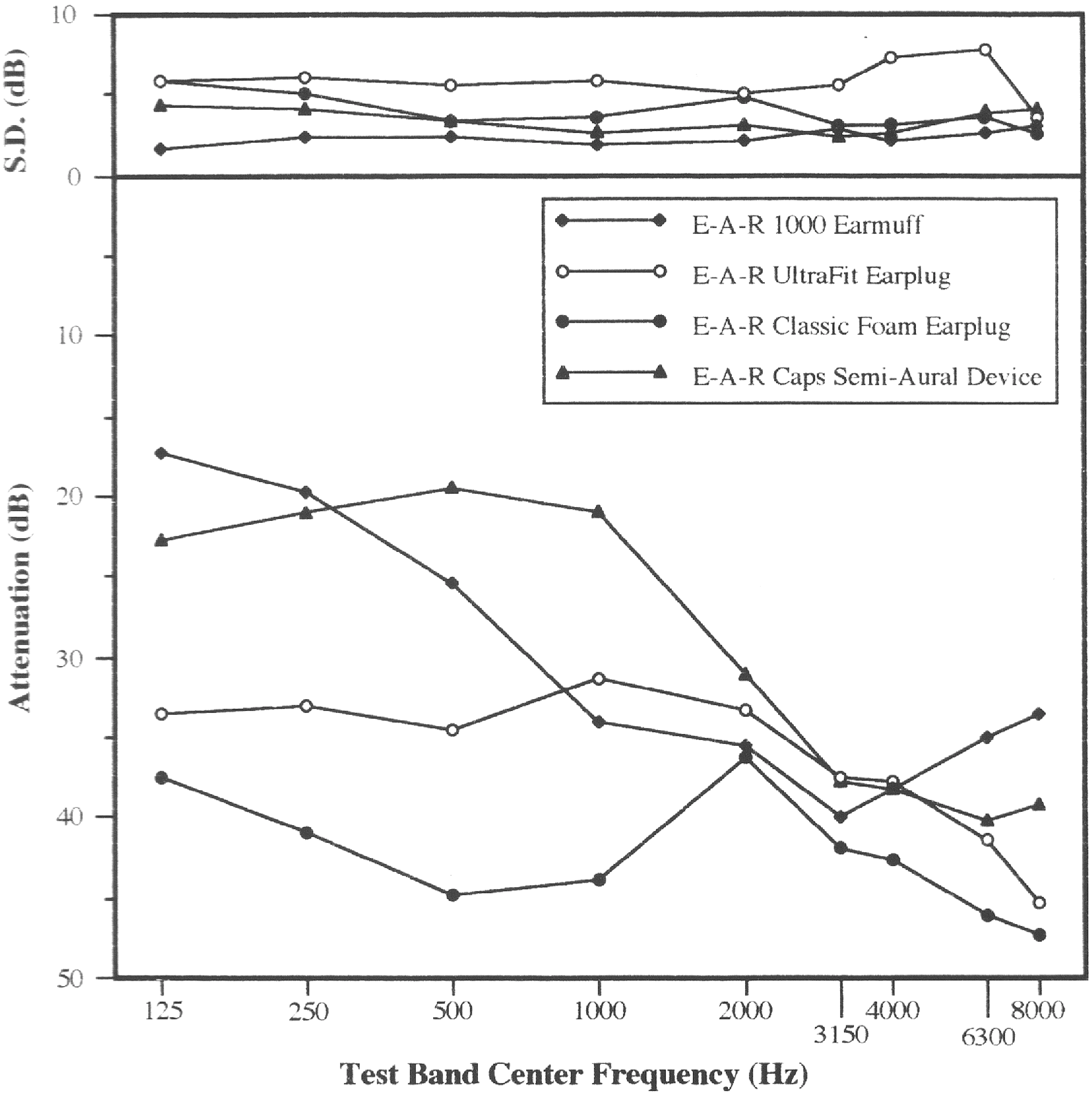


Figure 5. *Typical attenuation characteristics of various HPD types.* (from Robinson, 1993)

Custom-molded earplugs are made by obtaining an impression of the user's ear canal and then producing an earplug exactly matching this impression. While problems associated with sizing do not affect custom-molded earplugs, proper impressions are very important. In addition, while custom-molded earplugs do not provide attenuation levels as high as user-molded and pre-molded earplugs, they are less likely to be inserted improperly in field conditions and employees often are motivated to use them because they are "customized" for their own use (Berger, 1986).

Ear Canal Caps

Ear canal caps, or semi-aural devices, seal the ear canal at or near its rim. A headband is incorporated in the design to hold the ear caps in place. The headband can fit behind the head or under the chin, allowing greater versatility so that a proper fit is not compromised by eyeglasses, safety glasses, or other items of safety equipment that a worker may be wearing. Such devices are usually recommended only for intermittent use because they may be uncomfortable to wear for long periods, due to the force exerted by the cap on the ear canal entrance. The attenuation characteristics of ear canal caps also are not as good as most earplugs or earmuffs. In addition, the fact that they are often much more expensive than earplugs can also make them unappealing to employers (Berger, 1986).

Earmuffs

Earmuffs consist of two ear cups that surround the outer ear and seal against the side of the head connected by a headband or attached to a hardhat. An advantage of earmuffs over earplugs and ear canal caps is that they are more easily donned and doffed. Although earmuffs attenuate high-frequency noise better than do earplugs or ear canal caps, they generally do not attenuate low-frequency noise as well. Other disadvantages are that their fit is very much affected by jaw and head shape and they can impede the use of eyeglasses, hardhats, respirators, and other safety equipment.

The HPDs discussed above are categorized as passive hearing protection devices because they attenuate noise by incorporating structural features and mechanical elements to physically block the air conduction pathway to the ear (Casali, 1994). Passive HPDs attenuate the amplitude of both noise and any desirable sounds equally. Also, because they attenuate some frequencies more than others, they can alter the wearer's detection of sound and signals. Although traditional earmuffs perform well, providing about 20-40 dB of sound attenuation at frequencies above about 1000 Hz (Casali and Berger, 1996), they provide far less attenuation (0-20 dB) at frequencies from 125 Hz - 1000 Hz.

Active Noise Reduction HPDs

The active noise reduction (ANR) headset was patented by Paul Leug in 1936 (Nixon, McKinley, and Steuver, 1992). The theory of ANR is rather simple; however, due to limits in technology it has been difficult to implement until recent years. In theory, the original noise is sampled, an "anti-noise" is produced by the ANR circuitry with exactly the same amplitude but 180 degrees out-of-phase, and the two waves are superimposed resulting in cancellation of the noise. Due to limits in technology, however, the anti-noise may not have the exact amplitude of the original noise, which is one reason why there is some residual noise left, as can be seen in Figure 6. In addition, because of the geometric separation of the components of the system and the lags in the electronic circuit, there is a delay between the time the noise is sampled and the time the new, inverted wave is introduced. This delay causes waves at higher frequencies to be more out-of-phase, resulting in less attenuation (and even amplification) at higher frequencies.

ANR headsets can be classified as either open-back or closed-back, as shown in Figure 7. In open-back (supra-aural) devices, the ANR microphone/earphones are housed in a non-attenuating housing. These devices are lightweight and afford external hearing; however, if there is electronic failure, no hearing protection is provided by the device. Closed-back (circumaural) devices utilize earmuff style ear cups and cushions in the design to provide both active and passive attenuation. This type of design encompasses most of the ANR headsets on the market today.

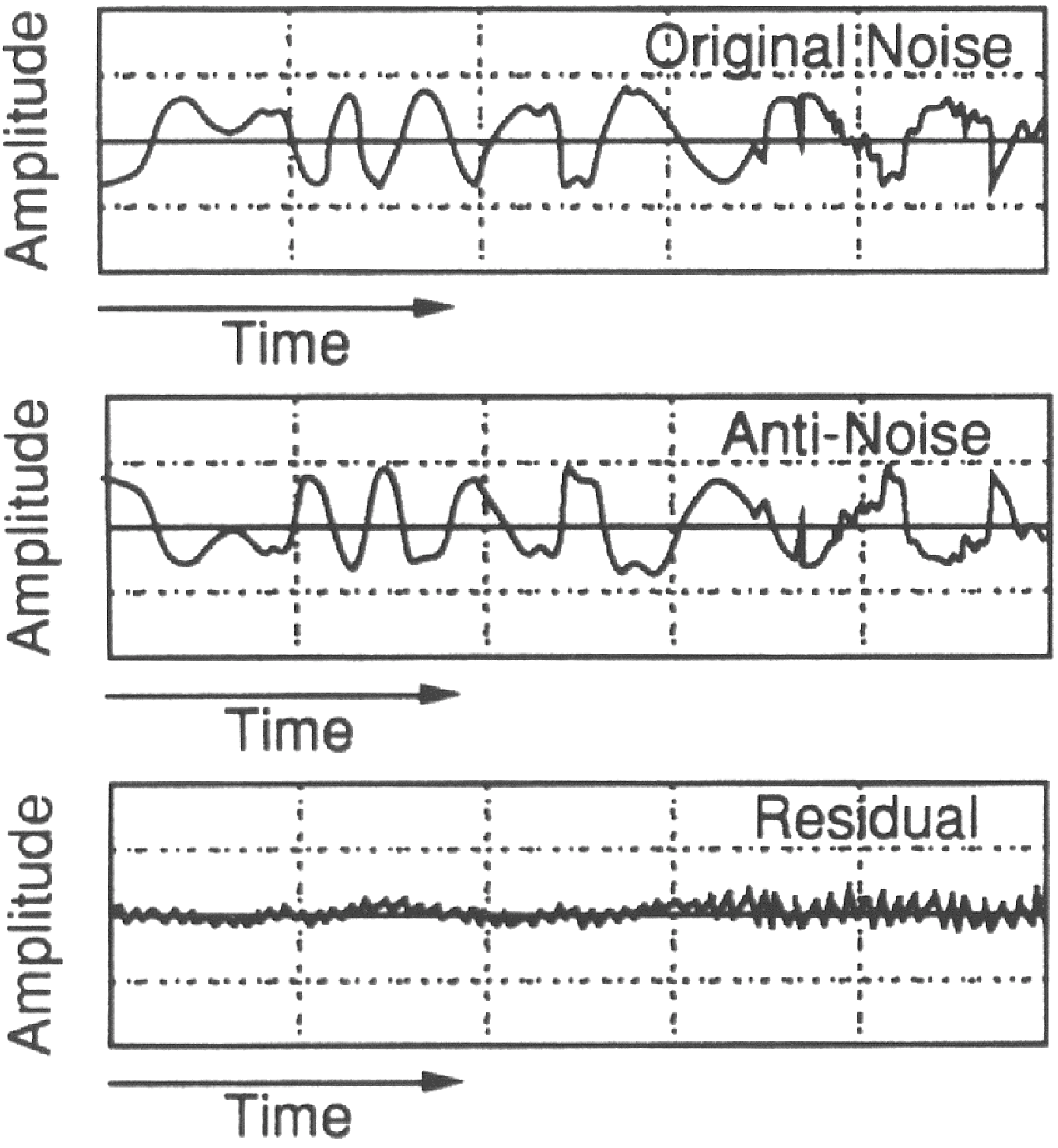


Figure 6. *Schematic of how ANR technology works (superposition of two waves).*

Circumaural ANR earmuff

Supra-aural ANR earmuff

Figure 7. *Examples of circumaural and supra-aural ANR devices.*

A study conducted by Nixon et al. (1992) evaluated the attenuation afforded by four circumaural ANR headsets and a supra-aural earmuff. In the study, the total and the passive sound attenuation for each headset was measured and the active attenuation component calculated (the difference between the total and passive attenuation). The results of the experiment indicated that at low-frequencies (100 Hz to 250 Hz), active attenuation for all of the circumaural earmuffs ranged from 15 dB to 22 dB. This was also the maximum active attenuation achieved over the entire frequency range from 100 Hz -10000 Hz. At higher frequencies (above 500 Hz), the devices provide little or no active attenuation, and in some cases, negative attenuation was found. The supra-aural earmuff showed no active attenuation at 100 Hz, maximum active attenuation of about 14 dB between 250 and 300 Hz, and zero attenuation above 2000 Hz. These results indicate that ANR provides improved attenuation at low frequencies. Combining the good low-frequency attenuation of active noise reduction with the good high-frequency attenuation of circumaural earmuffs could potentially result in an HPD with excellent broadband attenuation performance.

The previously discussed study only contrasted ANR headsets in active versus passive modes; however, a study conducted by Gower and Casali (1994) examined the attenuation of an ANR headset as compared to a passive headset. In this experiment, broadband pink noise presented at 102, 107, and 112 dBA and low-frequency bias tank noise presented at 102,107 and 112 dBA were used as background noise. The three different headset configurations used were a David Clark-passive earmuff and a BOSE-active earmuff with the electronics turned on and off. The results of this experiment indicated that the BOSE-earmuff with ANR operational produced better attenuation (up to 22 dB over the other headsets) at lower frequencies (below 600 Hz) than the other earmuffs. Although noise amplification occurred in the range from 800 to 4000 Hz in the headset with ANR operational, it still produced better attenuation than the David Clark passive earmuff.

CHAPTER 4: SIGNAL DETECTION WITH THE USE OF HPDS

Masking is a major problem that affects the audibility of warning signals in industrial settings. At high sound pressure levels, the ear distorts the auditory signal transmitted to the brain making it difficult for the listener to distinguish a desirable signal from the background noise. HPDs reduce this problem by reducing the overall level of noise (both signal and background noise) reaching the ear, making it easier for the brain to distinguish between signal and noise (Suter, 1989), in much the same way that sunglasses are used to reduce visual glare and allow the wearer to see things in greater detail. In fact, this *cochlear distortion* is often referred to as "acoustical glare."

Auditory Detection Under Passive HPDs

Wilkins and Martin (1977) performed an experiment that examined the effect of hearing protectors on the masked thresholds of acoustic warning signals. In their experiment, they presented two warning signals (a siren and a bell) in random noise at 75 dBC and 95 dBC to 16 subjects with normal hearing. There were a total of four conditions: an earmuff, an earplug, an electronic filter simulation of the attenuation provided by the earmuffs (1/3 octave band spectrum shaper), and an unoccluded condition. Results indicated that for both warning signals in the 95 dBC noise, masked thresholds were 3.34 dB higher in the unoccluded condition than the three protected conditions. The higher unoccluded masked thresholds were most likely due to cochlear distortion. In the 75 dBC noise, the results showed no difference in the masked thresholds between the unprotected and protected condition. This is not a problem, however, since HPDs are not recommended for such low-noise environments. No differences between the various protectors were found. The authors concluded that although the earmuffs had 15 dB greater mean attenuation than the earplugs, the earmuffs and earplugs had similar attenuation characteristics at certain frequencies; if the predominate signal energy is at those frequencies, no difference between the two types of HPDs will be found.

Wilkins and Martin (1982) conducted an additional study that examined the effects of hearing protection on the detection of warning sounds in noise. In the study, the masked threshold of 16 subjects was determined using the method of limits. Four warning sounds (a siren, a two-tone "high-low" warning sound, and the "high" and "low" components alone) were presented in two types of broadband background noise (workshop noise and random background noise) at 90 dBC. The two conditions were unoccluded and wearing earmuffs. The results of this second experiment indicated that the unoccluded condition produced significantly higher masked thresholds for only the siren and the “high-low” warning sounds. The reason that the individual “high” and “low” components did not produce a difference is because the signal did not contrast enough with the background noise.

In a study aimed at determining if an individual’s ability to detect warnings sounds in a ship’s engine room was affected by wearing hearing protectors, Forshaw (1977) conducted an experiment in which he asked subjects to detect a pure tone in two conditions, unoccluded and while wearing earmuffs. In his experiment, pure tones (ranging in frequency from 250 – 8000 Hz) were presented against continuous-spectrum engine noise at 88 dBA. The results indicated that wearing earmuffs lowered masked thresholds compared to the unoccluded condition, but the results were not statistically significant.

A study conducted by Coleman, Graves, Collier, Golding, Nicholl, Simpson, Sweetland, and Talbot (1984) measured the masked threshold of pure tones for miners wearing hearing protectors in the presence of mining noise (generally a low frequency noise) presented at approximately 92 dBA. The four conditions were: unoccluded, earmuff, helmet-mounted earmuff, and compressible foam earplugs. The mean threshold for each subject and condition was calculated over the entire frequency range of 500 Hz to 3000 Hz as well as for the following ranges: 500 – 1000 Hz, 1000 – 2000 Hz, and 2000 – 3000 Hz. For frequencies between 500-1000 Hz, there was an increase in threshold when earmuffs were worn (1.4 dB and 2.4 dB for earmuffs and helmet-mounted earmuffs respectively), thus requiring the warning signal to be presented at higher sound pressure levels when the listener was wearing these devices. Earplugs, however, did not show this effect. For frequencies above 1000 Hz, HPDs did not have a statistically significant effect on the mean masked threshold. It is important to note that the researchers did not find any significant difference between earplugs and the unoccluded condition over the entire frequency range. This is due to the excellent attenuation characteristics of earplugs at low frequencies (the noise was low frequency biased). In contrast, the poorer low frequency attenuation of earmuffs resulted in significantly higher masked thresholds.

Abel, Kunov, Kathleen, Pichora-Fuller, and Alberti (1983 and 1985) examined the effects of hearing protectors on detection of auditory signals in noise and in quiet. Both normal hearing subjects and those with noise induced hearing loss were tested while wearing earplugs and while unoccluded. The signals (1/3 octave bands of noise centered at 1000 Hz and 3150 Hz) were presented in three different noise conditions: quiet, mill-house noise (85 dBA), and rock-drill noise (85 dBA). In the two noise conditions, those subjects with normal hearing showed improved detection while wearing earplugs, meaning they could hear the signal at lower sound pressure levels while wearing HPDs as compared to the unoccluded condition. In quiet, however, their masked thresholds increased significantly when wearing earplugs. For the subjects with a hearing loss, the masked thresholds increased significantly with the use of hearing protection devices in all of the noise conditions.

A study conducted by Kerivan (1989) examined the effects of earplugs and earmuffs on the discrimination of changes in frequency of octave-band noises centered at 500 and 2000 Hz. The signals were presented at signal-to-noise ratios of 0, -3, and -6 dB in 70 dBA background noise (submarine engine room noise) via earphones. Attenuation characteristics of the earmuffs and earplugs were simulated by filtering both the noise and the signal. Robinson (1993) suggested the following problems with Kerivan's methodology: 1) use of manufactures' attenuation values rather than more realistic values and 2) the failure of the earphone presentation of the noise and signal to account for the "interaction between the subject and the sound field or among the HPD, sound field and the mechanism responsible for distortion" (Robinson, 1993). The reported results, however, support findings of other studies which used real earmuffs or earplugs (Abel et al., 1983; Wilkins and Martin, 1977). In all conditions that simulated HPDs, increased masked thresholds were produced compared to the unfiltered (unoccluded) condition. In addition, similar to results found by Coleman et al. (1984), simulated earplugs produced lower masked thresholds than did simulated earmuffs.

Other studies compared signal detection while wearing passive HPDs with other types of HPDs. However, the only one available for review is a study conducted by Casali and Wright (1995). In this study, the amplitude-sensitive earmuffs of both electronic and passive designs were evaluated against conventional passive earmuffs to determine if there was any improvement in signal detection. The four earmuffs used in the experiment were a passive mechanical amplitude-sensitive device, an electronic amplitude-sensitive device, and two conventional passive earmuffs. The background noise utilized in this study was pink noise presented at three levels (75, 85, and 95 dBA). The subjects (six males and six females with normal hearing) were required to detect a warning signal (a vehicle-mounted backup horn) in the presence of the background noise. The experimenters hypothesized that the amplitude-sensitive hearing protection devices would result in lower masked thresholds than the conventional devices. However, this was not the case, as the results indicated that there was no statistically significant difference in masked thresholds between the amplitude-sensitive HPDs and the conventional passive HPDs. The authors suggest that further research be conducted to examine the performance of these devices in higher noise levels and in intermittent noise, rather than continuous noise.

Auditory Detection under ANR HPDs

Few studies have addressed the detectability of auditory warning signals presented in noise while wearing active noise reduction HPDs. The majority of ANR studies have focused on attenuation characteristics and speech intelligibility. However, Abel and Spencer (1997) did conduct a study that examined the effect of ANR on a variety of auditory detection tasks.

The study used subjects with normal hearing as well those with mild to moderate bilateral sensorineural hearing loss (hearing thresholds equal to or less than 25 dBHL at 500 Hz and 30-65 dBHL at 4000 Hz). Each subject was tested in a total of six conditions: 1) unoccluded, 2) using EAR expandable foam earplugs, 3) using EAR pre-molded polymer triple flange HI-FI earplugs, 4) using Bilsom Viking earmuffs, 5) using Peltor 7004 earmuff without ANR operational, and 6) using Peltor 7004 earmuff with ANR operational. The signal was presented at a SPL of 80 dB for normal hearing subjects and 90 dB for the hearing-impaired subjects. The background noise used in the experiment was impulsive cable swagger (described as sounding like riveting) at 75 dB SPL for the normal hearing group, and 85 dB SPL for the hearing-impaired group. The increased noise and signal level for the hearing-impaired groups were due to that groups' inability to hear the signals while wearing the HPDs when the levels were the same as presented to the normal listeners. Hearing thresholds were determined for eight one-third octave noise bands centered at 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz at 80 dB and 90 dB, for normal hearing and hearing-impaired subjects.

For thresholds measured in noise, the signal-to-noise ratios required to detect the signal in background noise in the unoccluded condition did not change as a result of wearing hearing protectors. The Peltor 7004 with ANR operational did not perform significantly better than the other conventional HPDs. One possible reason for this result is that the noise levels were too low. Another reason is that ANR works best in low frequency noise, but the noise spectrum used in the experiment was not low-frequency biased.

CHAPTER 5: OTHER FACTORS THAT AFFECT SIGNAL DETECTABILITY WHILE WEARING HPDS

In addition to masking and HPD attenuation characteristics, several other factors affect a person's ability to hear auditory signals in noise. These factors include: comfort, attention (or inattention), warning signal characteristics, and hearing loss. Each of these factors is briefly discussed below.

Hearing Protector Comfort

Comfort is one of the most important factors in determining the amount of protection afforded by an HPD (Casali, Lam, and Epps, 1987; Park and Casali, 1991). If an HPD is uncomfortable, the worker may don and doff it repeatedly, resulting in a significant reduction in attenuation over an eight-hour day. For example, if discomfort causes an employee to remove his or her HPD for 15 min out of an 8-hr workday, the noise reduction rating would be reduced by 5 dB (assuming original NRR is 25 dB). This is a 20% reduction in protection from just 3% of non-wearing time (Park and Casali, 1991).

While there are no standard methods to collect comfort data, subjective measures are used most often (Wright, 1993). A rating scale was developed by Casali, et al. (1987), and has been validated in several studies (Casali, 1992; Casali and Grenell, 1990; Park and Casali, 1991). The comfort and acceptability rating scale is a multidimensional bipolar rating scale that assesses and quantifies the HPD wearer's subjective feelings. Numerical values (1-7) are assigned to each response and summed to compute the comfort index (CI). The CI then can be analyzed to determine if there are statistically significant differences between HPDs.

Attentional Demand

Although a sound may be audible, it may not always be detected. In particular, attentional demands (i.e., whether or not the listener is occupied with a task unrelated to listening for the sound) should be considered when evaluating detectability of a signal. The literature is unclear as to whether inattention elevates masked thresholds. In a study conducted by McGrath (1965), signal detectability with two concurrent vigilance tasks was examined. McGrath found that elevating the arousal of a subject while he or she is performing an easy task improves performance. However, adding a loading task and further increasing an already high arousal state involved with a complex task results in performance decrements.

In a study conducted by Wilkins and Martin (1982), subjects performed a loading task (video game) to ensure that their attention was directed away from the auditory detection task. Two conditions were represented: unoccluded and wearing earmuffs. The subjects were encouraged by continuous feedback and paid a bonus based on overall performance of both the loading task and auditory detection task. The results indicated that inattention did not increase the masked threshold of the unexpected sound. The results of this experiment may have been biased because the subjects were paid based on their performance.

In a study conducted by Fidell (1978), a driving task was stressed as being more important than the auditory detection task. Subjects were required to maintain a constant speed and, at the same time, turn the steering wheel of a test car in the direction of large red lights mounted on the front fenders. The results indicated higher masked thresholds (approximately 10 dB) when the subjects were occupied with the driving task. Thus, according to Fidell, inattention had a significant effect on detection of the auditory signal. This result differs from that reported by Wilkins and Martin (1982). The difference most likely is not due to an actual increase in the subjects' masked threshold but rather due to shifts in their criteria or changes in their decision rules.

There have been a limited number of studies that have examined the effect of inattention on a person's ability to detect a warning sound while wearing HPDs. The studies discussed above had methodological problems and conflicting results. In industrial settings, individuals are almost always performing another task rather than waiting in anticipation for a warning signal. For this reason, a simulated work task was included in the experimental paradigm used in this study.

Warning Signal Characteristics

Wilkins and Martin (1985, 1987) conducted a series of experiments to examine the role that the contrast of warning signals with both background noise and with other warning signals plays in a sound's masked threshold. Four different warning sounds were used in the experiment, each exhibiting different contrast characteristics as shown in Table 1. The tonal signal was composed of 3 pure tones (800, 2000, and 5000 Hz) and the random noise represented a 1/3 octave band of random noise centered at 2000 Hz. Each signal was presented to 16 subjects in broadband noise (75 dBC) and in quiet. The subjects performed a loading task similar to the one used in Wilkins and Martin (1984). The results indicated that both contrast variables, C_n

TABLE 1

Contrast Variables for Each Warning Sound

	High C_N*	Low C_N
High C_S**	Siren	Random Noise
Low C_S	Tonal Signal	Grinder

*C_N is Contrast to Noise

**C_S is Contrast to other signals

(contrast to noise) and C_S (contrast to other signals), were important factors related to the detection of warning sounds in noise.

Hearing Level

Hearing loss also is an important variable to control when performing experiments in the detection of auditory warnings. The results from several studies (Abel and Spencer, 1997; Abel et al., 1983; Abel et al., 1985; Coleman et al., 1984; Forshaw, 1977; Wilkins, 1984) indicate that subjects with moderate hearing loss are less likely to hear a warning signal with or without an HPD than are normal hearing subjects. When compared to subjects with normal hearing the results from these studies indicate raised masked thresholds for hearing-impaired subjects in all noise conditions regardless of whether the ear is occluded or unoccluded.

CHAPTER 6: RESEARCH OBJECTIVE

The objective of this experiment was to determine what advantages, if any, ANR earmuffs offer over conventional passive HPDs in allowing the wearer to hear auditory signals in the presence of noise. The experiment simulated noisy industrial environments by using a simulated work task along with warning signal and background noises with characteristics similar to those found in industry.

CHAPTER 7: EXPERIMENTAL DESIGN AND METHOD

Experimental Design

The overall experiment, depicted in Figure 8, will be discussed as two separate studies. The first part of the experiment, Figure 9, is a three-factor within-subjects design (three hearing protection devices tested at two noise levels in two types of background noise). The second part of the experiment, Figure 10, was conducted at only one noise level (85 dBA) but included an unoccluded condition.

Independent variables. The three independent variables represented in the design, all within-subject variables, were background noise spectra (NS), noise level (NL), and ear condition (EC). The two noise levels represented in the experiment were 85 and 100 dBA. This range encompasses about 90% of the noise levels commonly encountered in industry where HPDs are worn (Berger, 1986). Three different hearing protectors were used in the experiment: a standard user-molded foam earplug, a passive earmuff, and a circumaural ANR earmuff. In addition, an unoccluded condition was included at the 85 dBA noise level. There were no unoccluded conditions at 100 dBA due to the risk of doing permanent damage to the participants' hearing. Finally, two unique noise spectra were included in the experiment, pink noise (flat by octaves between 63 and 8000 Hz) and red noise, a more low-frequency biased noise with a C minus A value of 9 dB. These two noise spectra are illustrated in Figure 11.

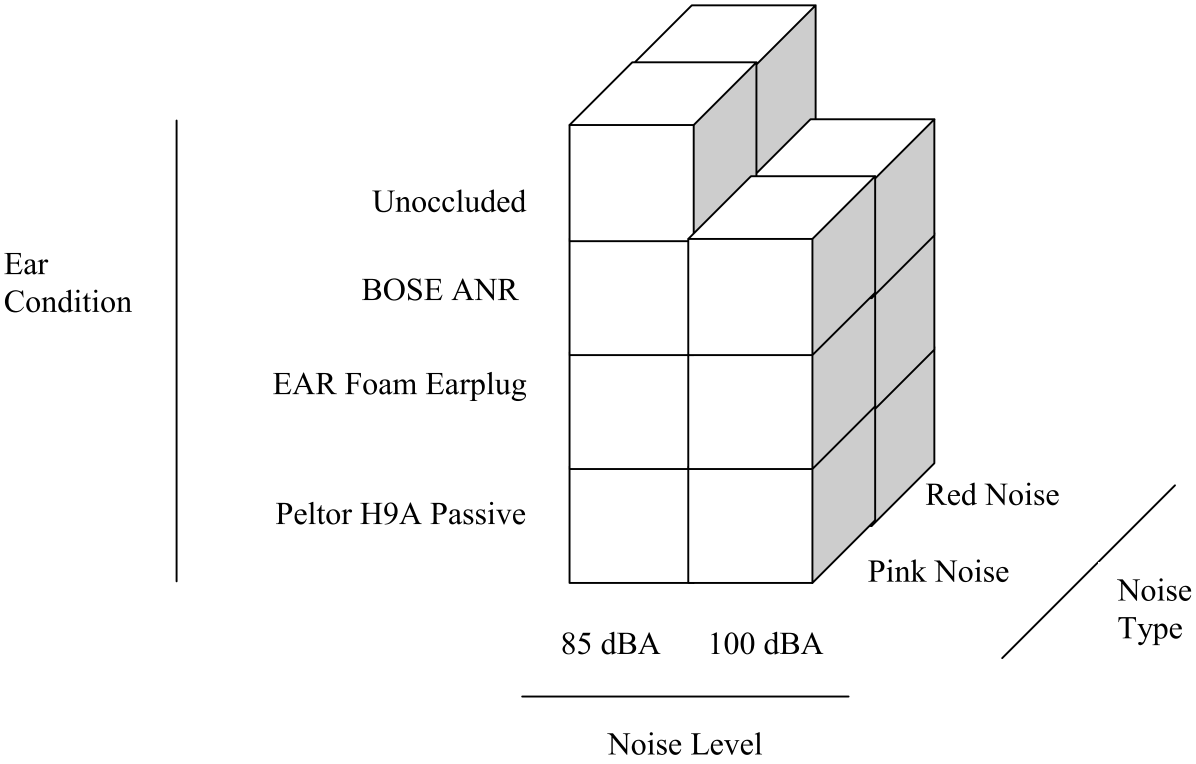


Figure 8. *The complete within-subjects experimental design.*

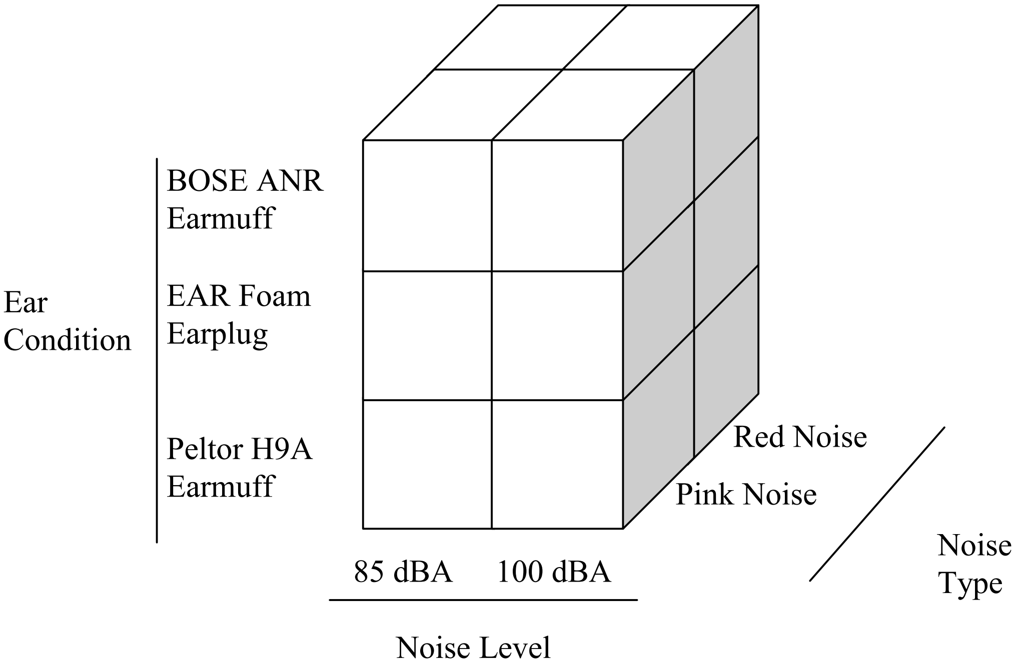


Figure 9. *Experimental design I.*

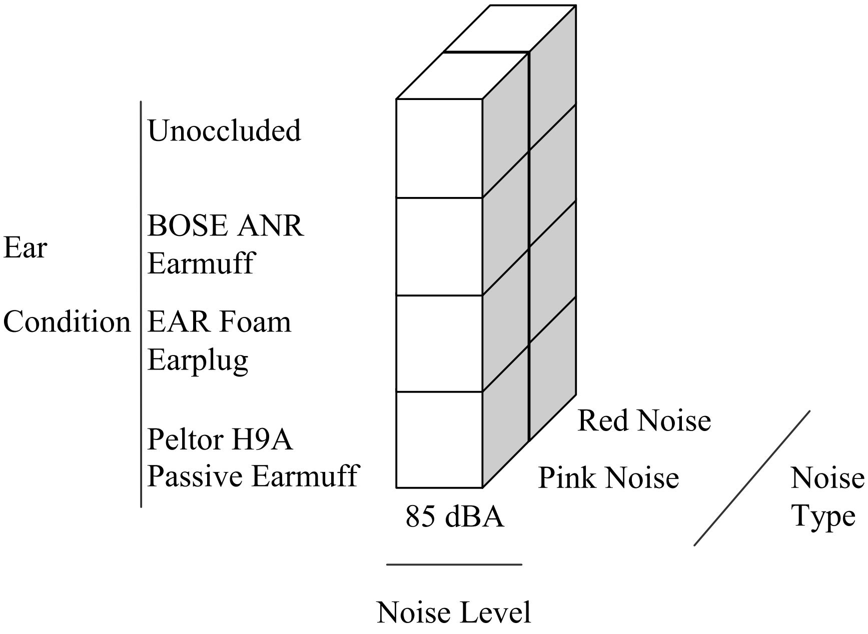


Figure 10. *Experimental design II.*

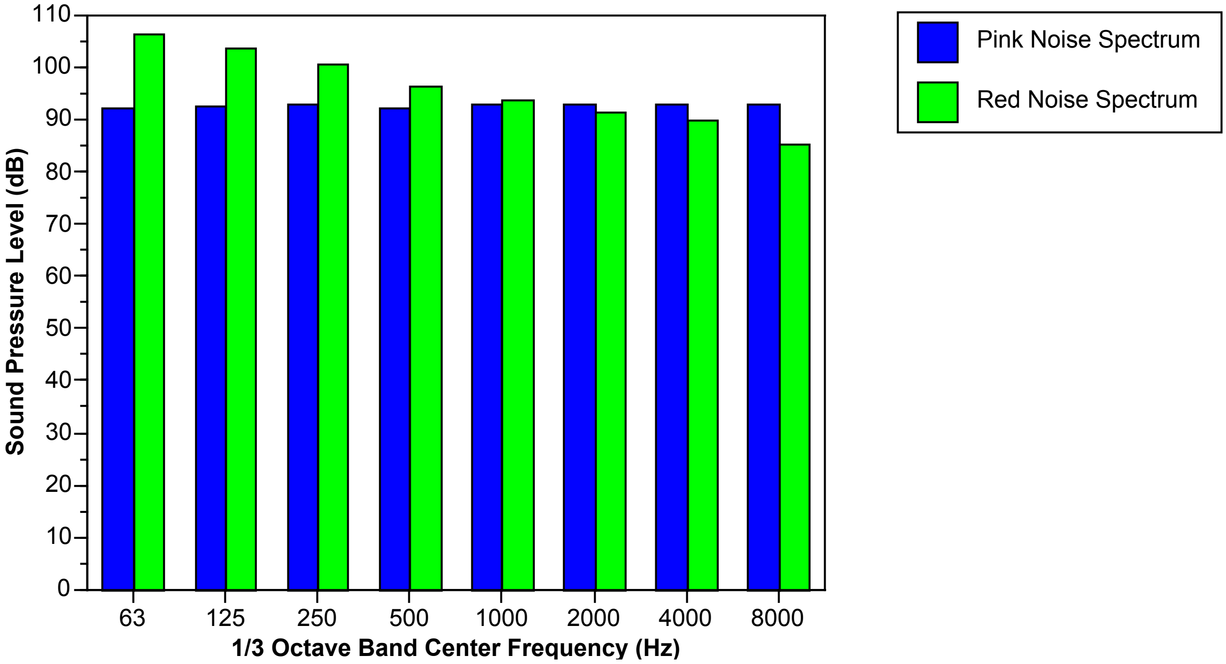


Figure 11. *Graphical comparison of the two noise spectra used in the experiment (pink and red noise) as measured in the experimental room.*

Dependent measure. The primary dependent measure was the masked threshold (in dBA) of the test signal. The A-weighting signal level was used rather than the unweighted (dB-linear signal level) because, while the backup alarm's energy was concentrated at frequencies ranging from 1000 – 2000 Hz, it was in reality a broadband noise. Furthermore, to compute appropriate signal-to-noise ratios, consistent units are necessary. Finally, A-weighted measurements are the most commonly performed industrial measurements. Masked thresholds were obtained by computing the arithmetic mean of the 19-25 correct positive responses in each treatment condition. The ascending Method of Limits (Gescheider, 1997) was the experimental paradigm used. Starting well below threshold, the signal level was increased in 2 dB steps, and decreased 10, 13, or 15 dB after a correct positive response. The detailed protocol for this process will be discussed later in the Experimental Procedure section.

In addition to masked thresholds, subjective ratings of the workload imposed by both the auditory detection task and the probability monitoring task (Haas, 1993) were collected at the end of each session using a Modified Cooper-Harper Scale (Wierwille and Casali, 1983), Appendix A. This subjective rating scale is highly correlated to objective measures of workload (Meshkati, Hancock, Rahimi, and Dawes, 1995). Subjective measures of HPD comfort and acceptability (using a seven-step bipolar comfort rating scale) also were obtained at the end of those sessions in which an HPD was worn. This rating scale, Appendix B, has been validated as a measure of hearing protector comfort (Casali, Lam, and Epps, 1987). After completing the entire experiment, subjects were asked to rank the three hearing protection devices with respect to the devices' perceived ability to facilitate hearing the signal.

Randomization. Each subject was exposed to four experimental conditions (two noise spectra at two noise levels each) in each experimental session, except for the two unoccluded sessions. The ordering of the four noise level/type combinations was randomly assigned to each subject for each session. The order of the five experimental sessions also was randomly assigned for each subject to prevent ordering effects from confounding the results. The two unoccluded conditions (conducted only at 85 dBA) were presented in two separate sessions to minimize the subjects' noise exposure.

HPD Selection

The three hearing protectors used in the experiment included the Noise Filter soft foam earplug, Figure 12 (manufactured by EAR, a division of AEARO Company), a Peltor H9A passive earmuff, Figure 13 (also manufactured by AEARO Company), and a BOSE ANR circumaural earmuff, Figure 14. The decision to use both a passive earmuff and a foam user-molded earplug was made based on the differences in their low-frequency attenuation characteristics. Earplugs typically attenuate low-frequency noise much better than do earmuffs, reducing the potential for upward spread of masking under the hearing protector. The low-frequency attenuation characteristics of the ANR headset approach those of the foam earplug. The attenuation characteristics of the three devices are shown in Figures 15 through 17.

Background Noise Spectra and Level

The two background noises used in this experiment were pink noise and red noise. The pink noise, Figure 18, was flat by octaves between 63 and 8000 Hz. Red noise is a low-frequency biased noise, whose spectra exhibits a C minus A value of approximately 9 dB, Figure 19. Both noise spectra were presented at broadband levels of 85 and 100 dBA. As mentioned earlier, these levels encompass approximately 90% of industrial noise exposure (Berger, 1986).

Figure 12. *Noise filter earplugs (manufactured by EAR, a division of AEARO Company).*

Figure 13. *Peltor H9A earmuff (manufactured by AEARO company).*

Figure 14. *BOSE ANR earmuff (manufactured by BOSE Corporation).*

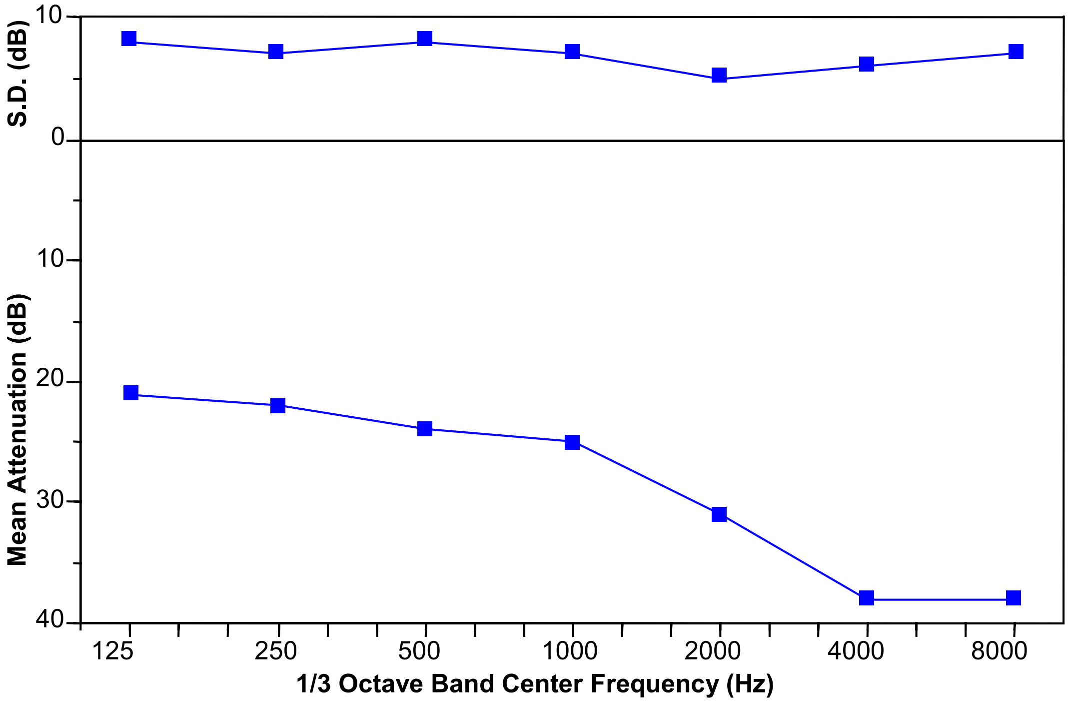


Figure 15. *Attenuation data for the EAR earplug (supplied by the manufacture on product packaging).*

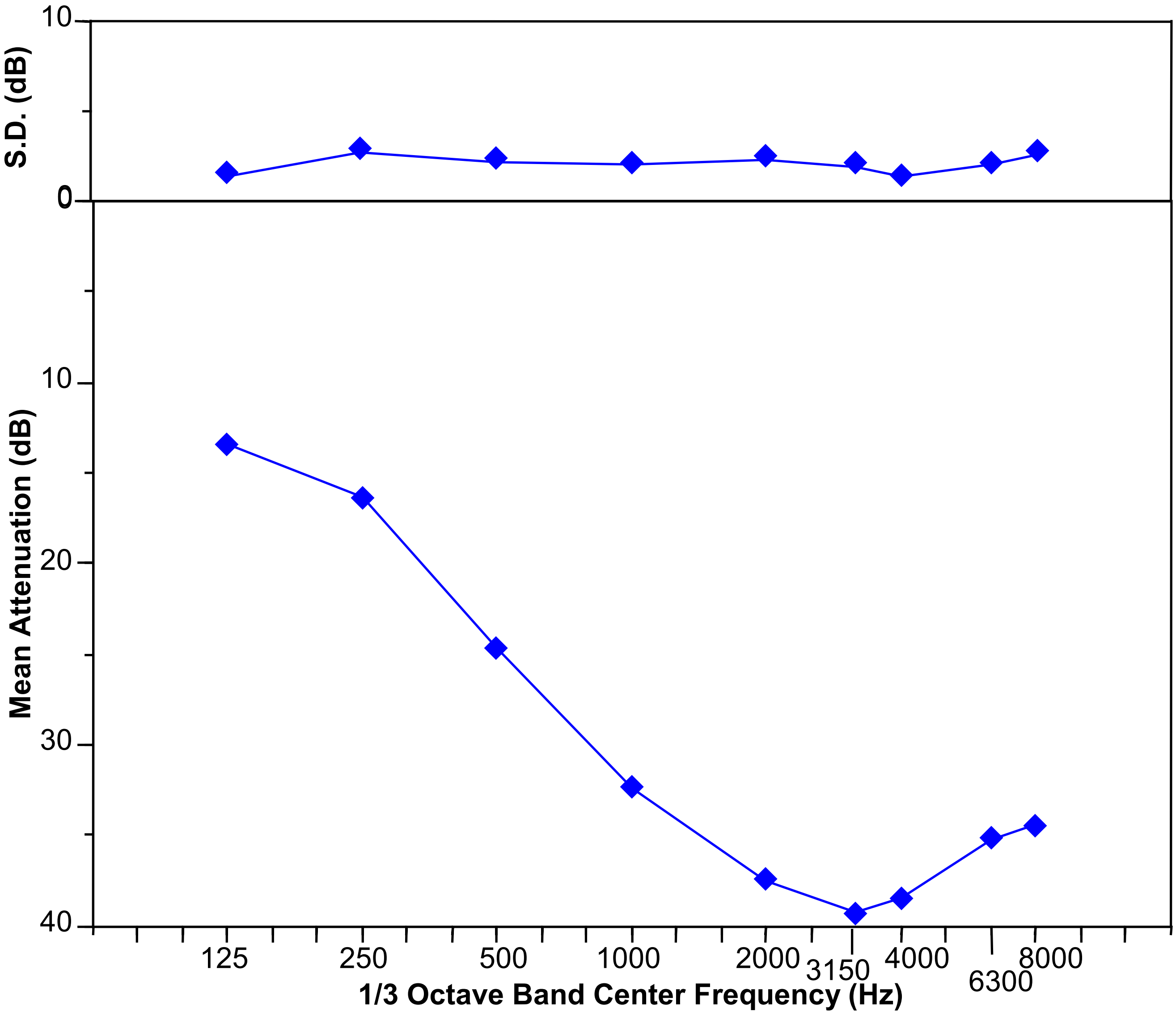


Figure 16. *Attenuation data for the Peltor H9A earmuff (supplied by the manufacturer).*

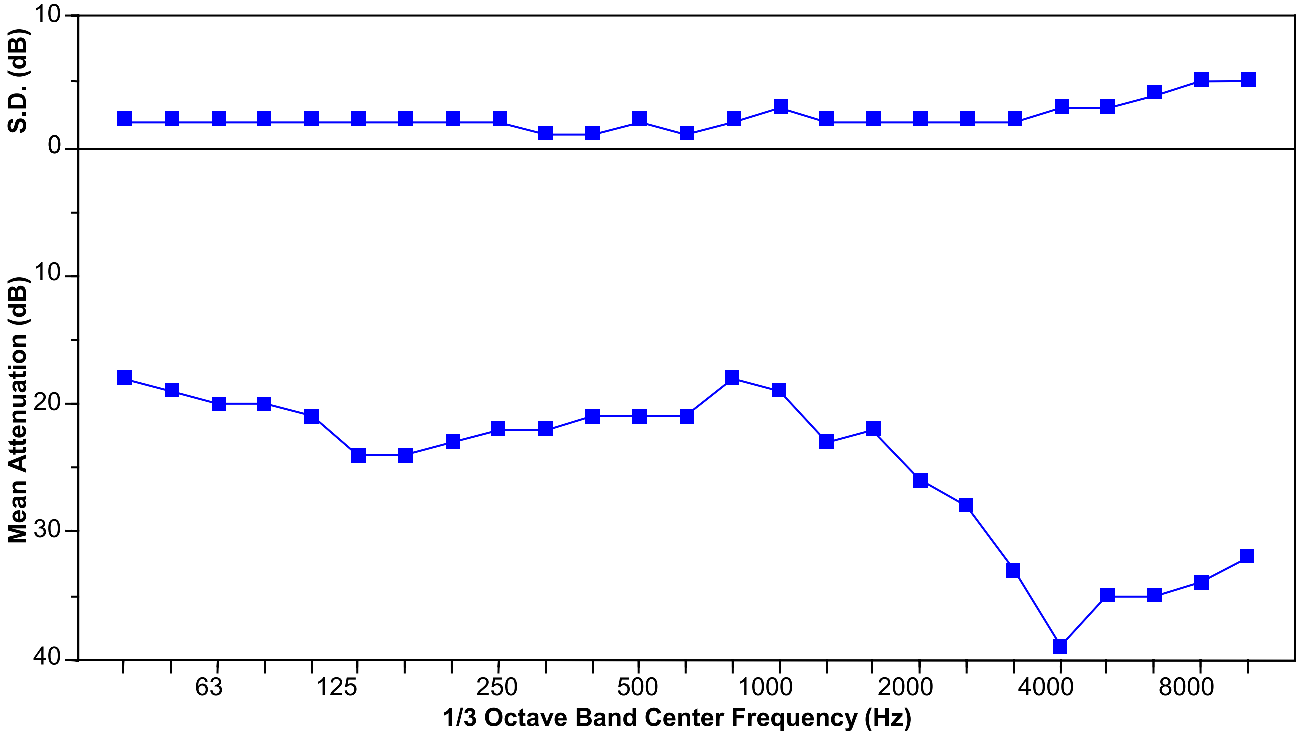


Figure 17. *Attenuation data for the BOSE ANR earmuff (supplied by the manufacturer).*

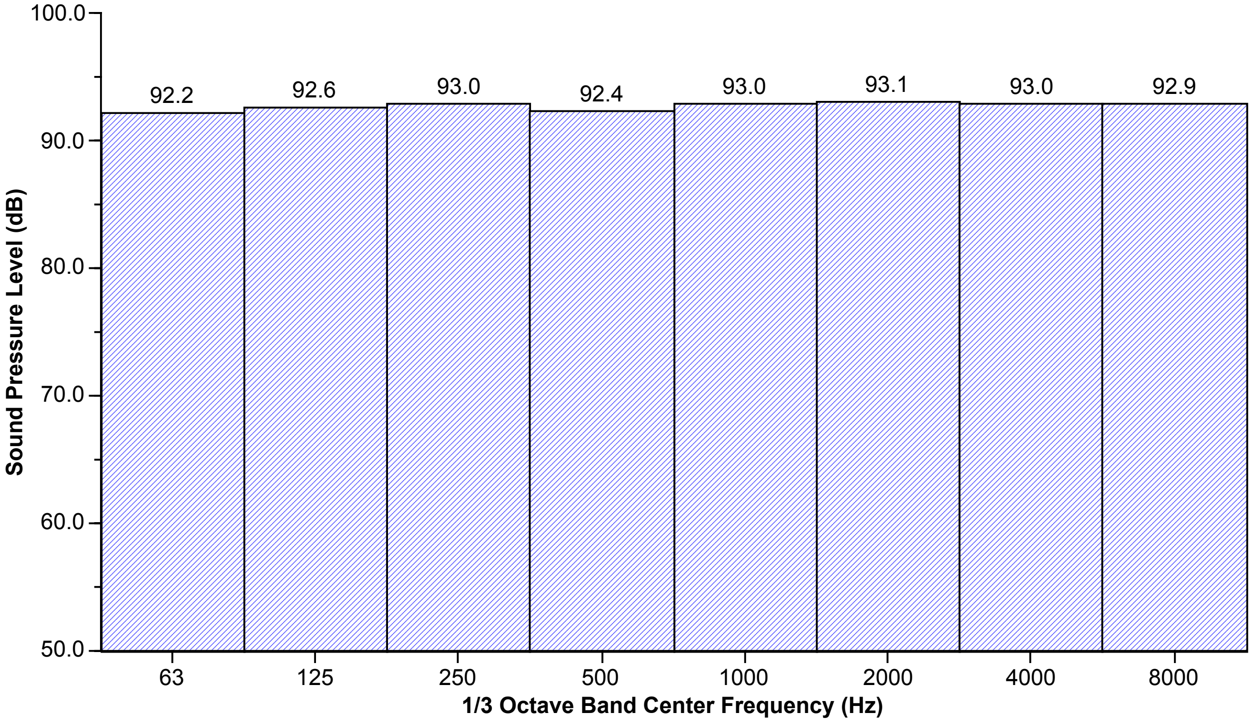


Figure 18. *Pink noise spectrum measured in the experimental room.*

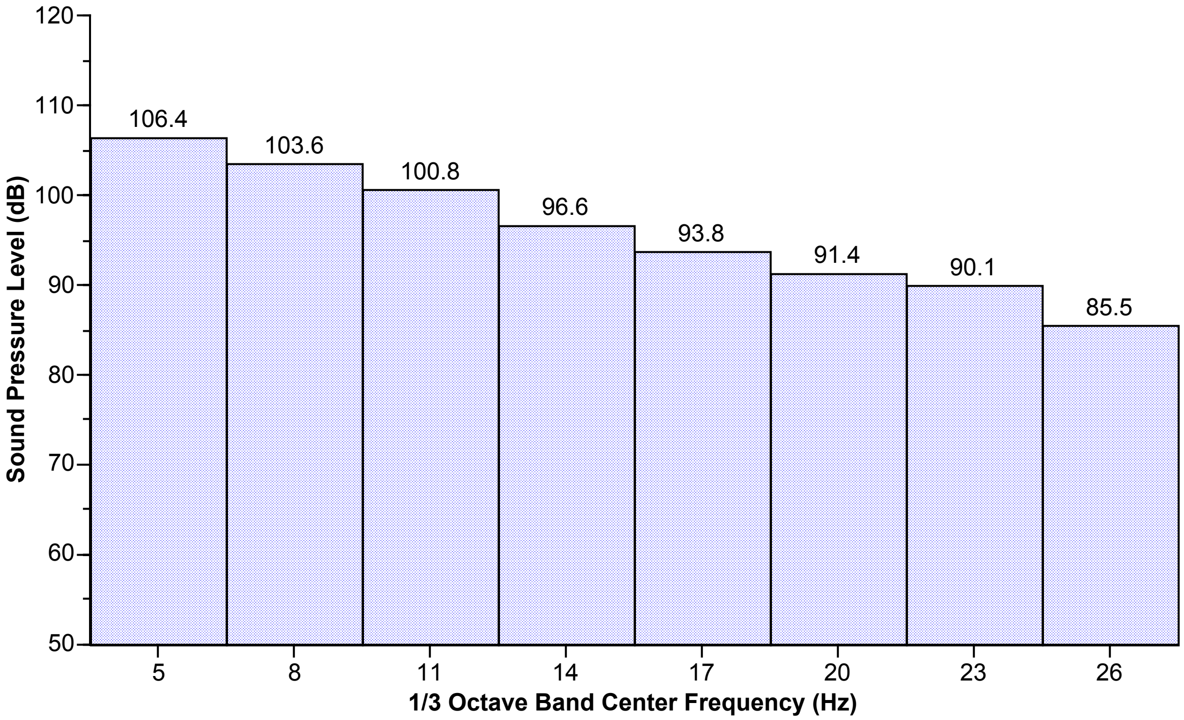


Figure 19. *Red noise spectrum measured in the experimental room.*

Warning Signal

The warning signal used in the experiment was a standard backup alarm (manufactured by Caterpillar, Part #3T-1815) used in both light and heavy equipment. The spectrum of the alarm is illustrated in Figure 20. This alarm was chosen not only because of its high contrast with the background noises used in the experiment, but also because it is typical of alarms found on many industrial and non-industrial vehicles (e.g. forklifts, front end loaders, school buses, and garbage trucks).

Subjects

Subjects included five male and five female volunteers between the ages of 18 and 49, recruited from the local Blacksburg and Virginia Tech communities. Each potential subject read and signed an informed consent form (Appendix C) per the requirements of the Virginia Tech Institutional Review Board (IRB) for Human Subjects in Research before beginning the screening procedures. The screening criteria included: an interview regarding ear history, current hearing health, prior experience with HPDs, an otoscopic examination, and a pure-tone audiometric examination. Only those individuals with hearing thresholds no greater than 20 dBHL at 125, 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz (in both ears) and for whom a visually-apparent quality fit could be achieved with all of the HPDs used in the experiment were asked to participate in the experiment.

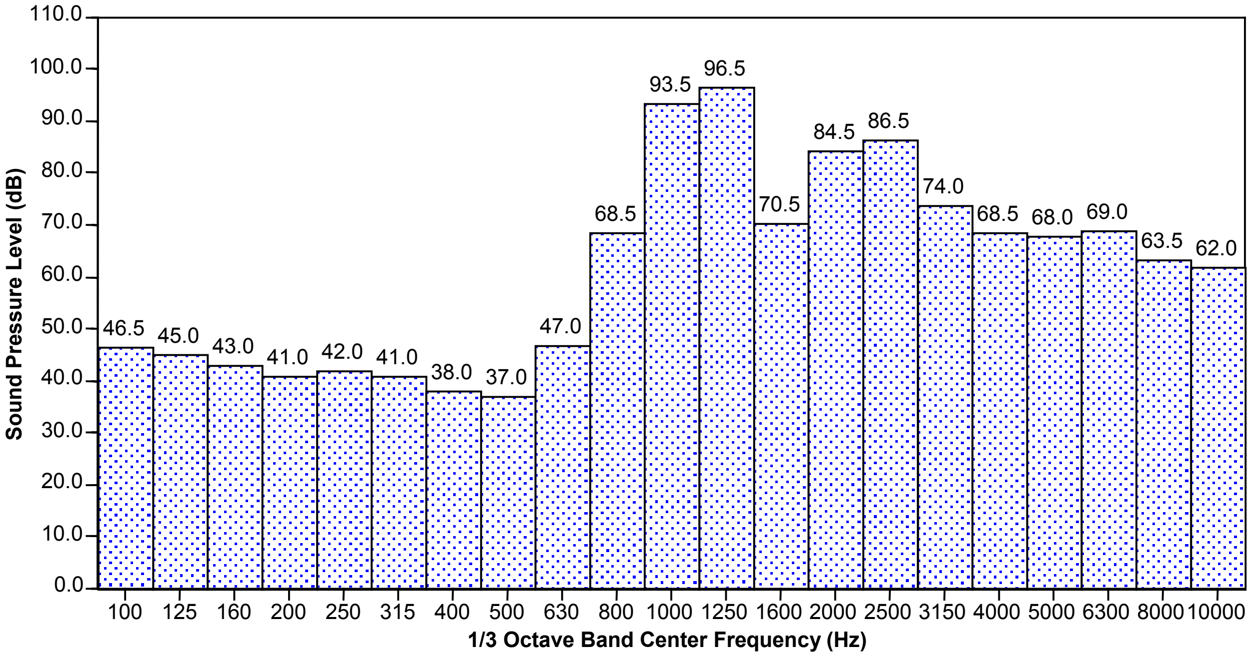


Figure 20. *Backup alarm spectrum.* (adapted from Robinson, 1993)

Facilities

The screening session took place in the Auditory Systems Laboratory, Room 538 Whittemore Hall. Audiometry was performed in the anechoic chamber located inside of the main laboratory. This facility offered a sufficiently quiet environment to obtain reliable, accurate audiograms (Casali, 1988; Casali and Robinson, 1990).

The experiment itself was conducted in the Auditory Systems Laboratory Annex, Room 519-N Whittemore Hall. This room provided a reasonably diffuse and non-directional sound field around the subject's head. This was verified by measuring the sound pressure level at six positions about the subjects' head center in accordance with ANSI S3.19-1974 (ANSI, 1974) as shown in Table 2.

Instrumentation

A photograph of the experimental setup is presented in Figure 21. The apparatus used to present the background noise is illustrated schematically in Figure 22. Pink noise was generated electronically using a Yamaha GE-60 Natural Sound Graphic Equalizer, which was also used to shape the pink noise spectrum. The red noise was presented using a TEAC-124 cassette tape player. An Audio Control Octave Equalizer was used to shape the red noise spectrum. The output of both equalizers was directed to an Adcom GFP-55 II pre-amplifier and to a pair of BOSE 1800V power amplifiers. One amplifier was used to drive four BOSE-802 series II full-range loudspeakers arranged around the subjects' location. The other amplifier was used to drive a BOSE 502B subwoofer that provided the necessary low-frequency excitation.

TABLE 2

SPL Variation at Six Positions About Head Center Position

1/3 OB Center	Right (-6,0,0)*	Left (6,0,0)*	R-L Δ **	Front (0,-10,0)	Back (0,10,0)	Up (0,0,6)	Bottom (0,0,-6)	6-Position Δ***
125	90.0	90.3	0.3	90.1	89.9	89.6	89.6	0.7
250	91.3	90.7	0.6	89.6	89.5	89.5	88.0	3.3
500	88.5	90.3	1.8	90.5	88.4	88.2	88.2	2.3
1000	89.1	89.0	0.1	90.8	88.2	89.3	89.0	2.6
2000	88.0	83.8	1.2	90.5	87.9	88.9	88.1	3.7
4000	89.4	89.0	0.4	90.4	90.0	90.4	89.2	1.4
8000	88.4	88.8	0.4	89.7	89.7	89.6	86.7	3.0

*All dimensions are in cm.

**Absolute value dB difference between right and left microphone positions.

***Maximum absolute value dB difference between all pairs of the 6 microphone positions.

Figure 21. *Experimental facility.*

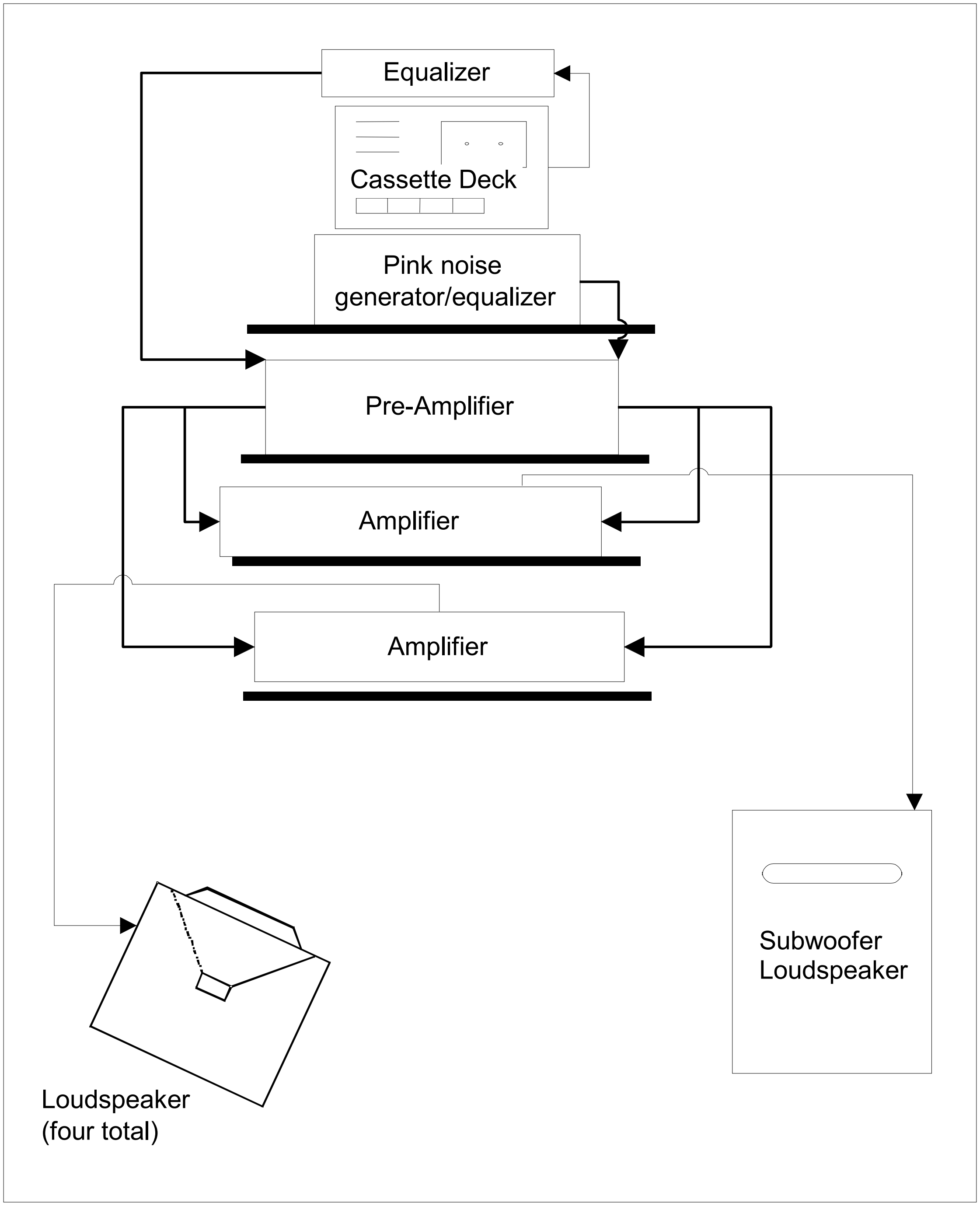


Figure 22. *Schematic of background noise presentation system.*

The system used to present the warning signal, illustrated in Figure 23, was separate from the system used to present the background noise. The warning signal was presented via a Power Macintosh 8500 computer with the computer's audio output directed to a Beltone 2000 audiometer. An NAD 1020B pre-amplifier and NAD 2200 power amplifier were used to amplify the signal which was output to a single Klipsch K-57K midrange loudspeaker. The signal level was controlled manually by the experimenter using the calibrated attenuator circuits in the Beltone 2000 audiometer.

An IBM-AT computer, Figure 24, was used to control the probability monitoring task. The probability monitoring task was presented on the computer's monitor while a modified numeric keypad (unused keys were removed and the covered with balsa wood) was used as the subjects' response switch. A separate response button allowed the subject to respond to the auditory detection task. The experimenter used a second monitor and keyboard connected to the IBM-AT computer to initiate and terminate the probability monitoring task. The experimenter's workstation is shown in Figure 25

Calibration Procedure for Noise and Signal Systems

Prior to each experimental session and each treatment condition, the Larson-Davis (L-D) 3200 spectrum analyzer was used to verify the appropriate sound pressure level (85 dBA or 100 dBA) and to check the noise spectra. For these measurements, the microphone was located at the subjects' head center position. The L-D 3200 also was used to monitor the sound pressure level (SPL) within the test space during the experiment.

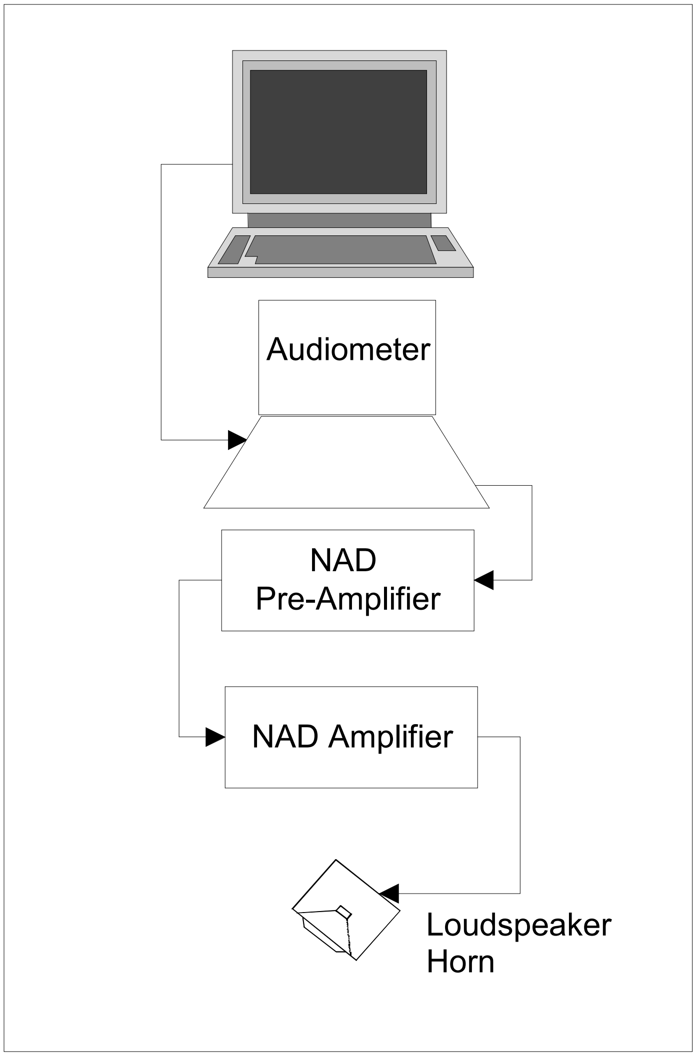


Figure 23. *Schematic of warning signal presentation system.*

Figure 24. *Subject workstation.*

Figure 25. *Experimenter workstation.*

The sound pressure level of the signal was calibrated by always setting it 20 dBA above the reading on the Beltone 2000 Audiometer. A L-D 800B sound level meter was used for this purpose. This procedure involved setting the attenuator of the Beltone to 70 dBHL and adjusting the amplifier volume control so that the peak signal level was 90 dBA (as read on the L-D 800B in L_{peak}). True masked thresholds were subsequently obtained by adding 20 dB to the reading from the Beltone audiometer.

Experimental Procedure

Each subject attended a combined screening/training session and five experimental sessions. During their initial visit, prospective subjects underwent the screening procedures, and if they qualified, were trained in the experimental procedures. This screening/training session lasted approximately 1½ hours. Each of the three experimental sessions for the occluded conditions lasted about 2 hours and the two experimental sessions for the unoccluded conditions lasted about ½ hour each.

Subject screening and training. The screening session began in the Auditory Systems Laboratory, Room 538, Whittemore Hall on the Virginia Tech campus. The screening protocol is shown in Table 3. At the beginning of the screening session, the potential subject was given both a written (i.e., the Informed Consent Form, Appendix C) and verbal description of the experiment. If the subject was still interested in participating in the experiment, his or her physical auditory health was evaluated by way of a questionnaire and an otoscopic examination (a visual examination of the external ear and ear canal using an otoscope) to ensure he or she did not have any obvious problems with his or her ears such as excessive earwax or an ear infection. If the potential subject's auditory health was acceptable, a pure-tone audiogram was then performed. (Screening forms appear in Appendix D.)

TABLE 3

Protocol for Subject Screening

1. The experimenter greeted the prospective subject.
2. The prospective subject read and signed the Informed Consent form.
3. The experimenter gave the prospective subject a verbal description of the experiment and screening procedures.
4. The experimenter asked the prospective subject several questions about his or her auditory health.
5. The experimenter performed an otoscopic examination on the prospective subject.
6. The experimenter performed a pure-tone audiogram on the prospective subject, while he or she was sitting in the anechoic chamber.

As stated previously, the pure-tone audiogram (conducted at frequencies of 125, 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz) was performed in the laboratory's anechoic chamber. Subjects who did not meet the hearing level requirements (hearing threshold levels no greater than 20 dBHL in both ears at the frequencies specified above) were excused. Those subjects who did qualify and chose to participate in the study proceeded to the training phase of the screening/training session.

The training session, as well as the experiment itself, was conducted in the Auditory Systems Laboratory Annex, Room 519-N Whittemore Hall. The protocol for the training portion of the session appears in Table 4. The subject was ultimately required to perform both the auditory detection task and the visual probability monitoring task simultaneously.

The probability monitoring (Haas, 1993) task consisted of four rectangular gauges, with pointers, presented on a computer monitor. Under normal circumstances, the pointer on each gauge moved from one side of the centerline to the other in a random fashion. At random times, the pointer would remain on one side or the other of the gauge centerline 95% of the time. The subject's task was to monitor each of the gauges and press the response key corresponding to the "biased" gauge, when this non-random behavior occurred. The computer recorded the number of correct and incorrect responses as well as response times (measured from the time a gauge pointer became biased to the time the subject responded).

TABLE 4

Protocol for Subject Training

1. The experimenter gave the subject a verbal description of the probability monitoring task.
2. The experimenter demonstrated the probability monitoring task.
3. The subject performed two, 3-minute practice trials of the probability monitoring task.
4. The experimenter then explained the procedures for the auditory detection task.
5. The subject was fitted with a Peltor H9A earmuff, similar to the one used in the experiment, but not the same model.
6. The subject practiced the auditory detection task, by itself, in quiet for 4 trials.
7. The subject practiced the auditory detection task, by itself, in noise for 4 trials. (The noise level was 75 dBA, which was lower than those levels used in the experiment.)
8. The subject practiced both the probability monitoring task and the auditory detection task together, in noise, for one 10-minute trial, performing both tasks simultaneously.

The auditory detection task was conducted using the ascending Method of Limits (Gesheider, 1985). This is a common technique for determining sensory thresholds and was chosen because it is efficient and yields accurate results. The signal was initially presented at a level well below the subject's masked threshold and increased in 2 dB increments until the subject indicated the presence of the signal. The signal level was then decreased 10, 13, or 15 dB before again being increased in 2 dB steps. This process was repeated for 10 minutes and yielded approximately 10 correct positive responses. Each noise level/type condition was repeated twice to obtain about 20 correct positive responses for each noise level/type combination.

Data collection session. The experiment consisted of five sessions, one for each occluded condition and two for the unoccluded conditions. Each occluded session contained all four combinations of background noise level and spectrum for a specific hearing protector. This was done to prevent hearing protection fit from confounding the data. Separate unoccluded sessions were conducted for each background noise spectrum to minimize any risk of permanently damaging a subject's hearing.

Prior to each data collection session, both the background noise level and the backup alarm level were set as previously described. The subject's task during the experimental sessions was to indicate when he or she heard the auditory signal by pressing a button positioned on the desk in front of them. In addition to listening for the auditory signal, the subject performed the visual probability monitoring task. The purpose of this secondary task was to better represent industrial situations in which people are attending to their jobs rather than listening intently for an auditory signal. The subject was instructed that both tasks were of equal importance.

After each session, the subject completed a workload assessment, Appendix A. The Modified Cooper-Harper scale (Wierwille and Casali, 1983) was used to evaluate the workload imposed by both the probability monitoring task and the auditory detection task. Mental workload was of interest to ensure the probability monitoring task provided a sufficient amount of attentional demand. Each subject also was asked to complete a comfort assessment of the hearing protection device (if applicable) using a seven-step bipolar comfort rating scale, Appendix B. At the end of the last session, the subjects ranked each hearing protection device according to its ability to facilitate their ability to hear the signal. The experimental protocol is summarized in Table 5.

TABLE 5

Protocol for Data Collection Session

---

1. The experimenter gave the subject a verbal description and procedures of the experiment.
2. The experimenter fit the subject with a hearing protection device (except for the two unoccluded sessions).
3. The subject was seated at the computer.
4. The experimenter initiated the noise.
5. The experimenter initiated the probability monitoring task from her workstation.
6. The experimenter began the auditory detection trials.
7. The subject performed two, 10-minute trials of the auditory detection task and the probability monitoring task for each noise type/level condition.
8. After each 10-minute trial, the experimenter stopped the noise.
9. At the end of two trials, the subject was asked to step outside the room while the experimenter prepared for the next noise type/level condition.
10. Steps 3 through 9 were repeated until each noise type/level condition were completed.
11. The subject was asked to rate the subjective comfort of the hearing protection device using the scales shown in Appendix B.
12. The experimenter removed the hearing protection device from the subject.
13. The subject completed a survey assessing his or her mental workload during the session, using the questionnaire located in Appendix A.

CHAPTER 8: DATA ANALYSIS

Generation of Masked Thresholds

Masked thresholds in (dBA) for each subject were obtained by calculating the arithmetic mean of all correct positive responses (19-25) in each noise type/level condition. The means and standard deviations (in dBA) for each experimental condition across all ten subjects appear in Table 6. The data were analyzed as two separate experiments because the unoccluded conditions were only conducted at 85 dBA. The first analysis examined the hearing protection devices at all noise levels and noise types while the second analysis examined all ear conditions including the unoccluded conditions, only at 85 dBA for both types of noise. These analyses are consistent with the experimental designs illustrated in Figures 10 and 11.

First Analysis

A repeated measures analysis of variance (ANOVA) was used to examine main effects of ear condition (EC), noise level (NL), noise spectrum (NS), and all of the associated interactions. One of the main assumptions made when performing a repeated measures ANOVA is homogeniety of covariance. To guard against any violation of the assumption of homogeniety of covariance, Geisser-Greenhouse corrections were used. This correction was only made for Ear Condition and its appropriate interactions because heterogeneity of covariance occurs only in factors with more than two levels (Winer, Brown, and Michels, 1991). The dependent variable in the analysis was the mean masked threshold, in dBA. The results of the ANOVA are summarized in Table 7.

TABLE 6

Mean (Standard Deviation) for Threshold Data

	Noise type and level			
HPD	**Pink noise at 100 dBA**	**Pink noise at 85 dBA**	**Red noise at 100 dBA**	**Red noise at 85 dBA**
Earmuff	91.00	73.46	98.93	77.11
	(3.35)	(3.95)	(2.65)	(3.24)
Earplug	90.03	75.45	92.36	77.51
	(2.12)	(2.52)	(2.30)	(2.40)
ANR earmuff	92.65	74.40	95.01	76.34
	(3.27)	(2.91)	(3.02)	(4.06)
Unoccluded		77.79		81.56
		(2.61)		(2.89)

TABLE 7

ANOVA Summary Table for Primary Analysis (values in bold type indicate significance)

Source	df	MS	*F*	*p*	G-G *p*
Between -Subjects					
Subjects (S)	9				
Within-Subjects					
Ear Condition (EC)	2	23.2958	1.64	0.2214	0.2239
EC X S	18	14.1937			
Greenhouse-Geisser Epsilon = 0.9255					
Noise Spectrum (NS)	1	308.1992	162.55	**0.0001**	
NS X S	9	1.8961			
Noise Level (NL)	1	9496.0170	3510.17	**0.0001**	
NL X S	9	2.7053			
EC X NS	2	32.5425	8.51	**0.0025**	**0.0053**
EC X NS X S	18	3.8227			
Greenhouse-Geisser Epsilon = 0.8044					
EC X NL	2	77.2362	19.38	**0.0001**	**0.0001**
EC X NL X S	18	3.9853			
Greenhouse-Geisser Epsilon = 0.9757					
NS X NL	1	12.8525	4.90	0.0541	
NS X NL X S	9	2.6235			
EC X NS X NL	2	7.3490	5.03	**0.0184**	**0.0192**
EC X NS X NL X S	18	1.4607			
Greenhouse-Geisser Epsilon = 0.9786					

Interactions. Statistically significant ($p \leq 0.05$) interactions included: EC X NL (F = 19.38, $p_{\text{G-G}} = 0.0001$) and EC X NS (F = 8.51, $p_{\text{G-G}} = 0.0053$). Post-hoc analyses of these interactions were conducted using simple effect F-tests followed by a Student Newman-Keuls test. Results of the simple effect F-tests indicated that the simple main effect of ear condition was significant at 100 dBA (F=23.00, $p < 0.0001$) but not at 85 dBA. The simple main effect of ear condition was also significant for red noise (F = 13.00, $p < 0.0001$) but not for pink noise. Furthermore, the simple main effects of both noise level and noise spectrum were significant for all of the types of hearing protection devices (EC).

A Student Newman-Keuls test then was conducted to determine the specific location of each of the simple effects. Based upon the results of this analysis, the Peltor H9A earmuff produced significantly higher ($p \leq 0.05$) thresholds in red noise (88.0 dBA) than the EAR earplug (84.3 dBA) and the BOSE ANR earmuff (85.7 dBA), Figure 26. In 100 dBA noise the EAR earplug produced significantly lower masked thresholds (91.9 dBA) than either the BOSE ANR earmuff (93.8 dBA) or the Peltor H9A earmuff (95.5 dBA), while the BOSE ANR earmuff produced significantly lower masked thresholds than the Peltor H9A earmuff, Figure 27.

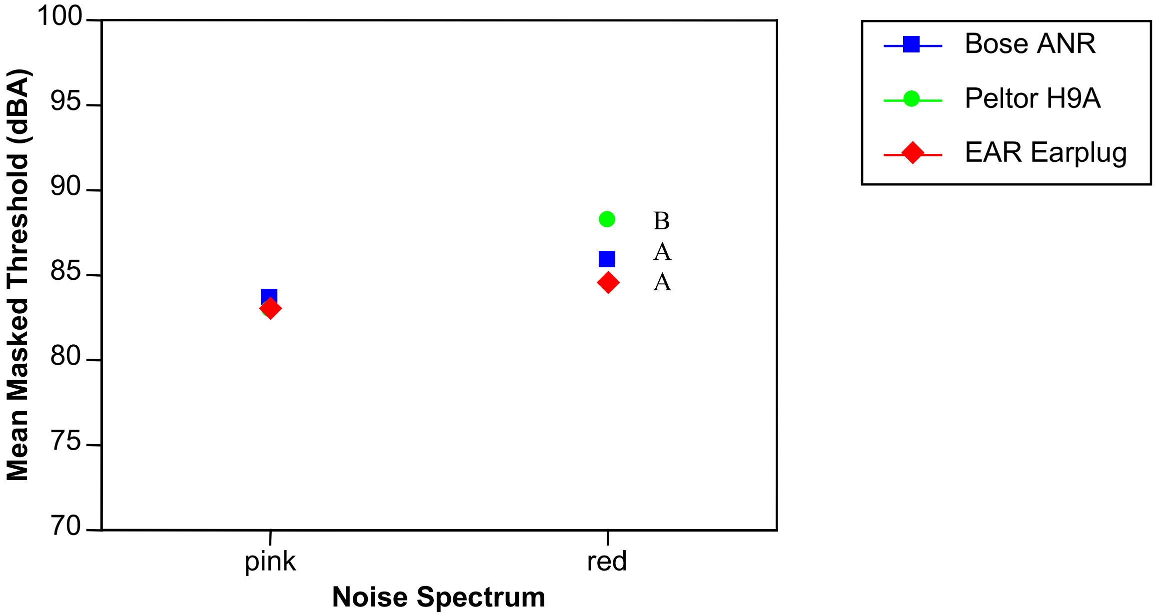


Figure 26. *Ear condition by noise spectrum interaction. (Means with the same letter are not significantly different, p≤0.05 for a given noise spectrum.)*

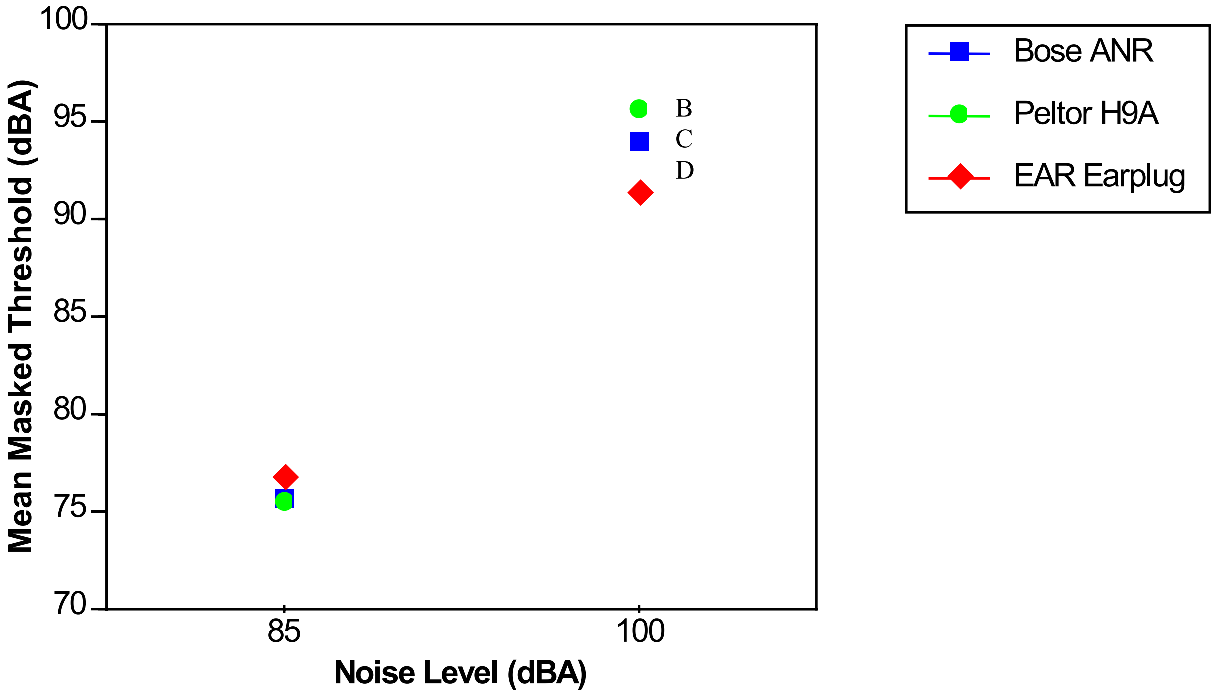


Figure 27. *Ear condition by noise level interaction. (Means with the same letter are not significantly different, p≤0.05 for a given noise level.)*

Main effects. Significant main effects included noise level and noise spectrum both significant at ($p \leq 0.0001$), Figure 28. For all hearing protection devices (EC) masked threshold were significantly ($p \leq 0.0001$) higher in 100 dBA (93.5 dBA) than in 85 dBA noise (75.7 dBA). Masked thresholds were also significantly higher ($p \leq 0.0001$) in red noise (86.2 dBA) than in pink noise (83.0 dBA), Figure 29.

Second Analysis

The second ANOVA included the unoccluded condition in addition to the occluded conditions, but only at 85 dBA. The ANOVA summary table is presented in Table 8. Again, the Greenhouse-Geisser correction was used to account for heterogeneity of covariance where appropriate. The main effects of ear condition and noise spectrum were found to be significant (EC: $F = 7.91$, $p = 0.0007$; NS: $F = 65.27$, $p = 0.0001$). The Student Newman-Keuls post-hoc test revealed that the unoccluded condition produced significantly higher masked thresholds (83.07 dBA) compared to the BOSE ANR earmuff (79.48 dBA), the Peltor H9A earmuff (79.41 dBA), or the EAR earplug (80.40 dBA). However, the masked thresholds for the occluded conditions were not significantly different from each other. These results are summarized in Figure 30 and Table 9. As in the primary analysis, noise spectra was also found to be significant ($p = 0.0001$) with the pink noise spectrum yielding lower masked thresholds (95.3 dBA) than the red noise spectrum (98.1 dBA).

Comfort and Acceptability Analysis

The data from the comfort and acceptability questionnaire were used to calculate comfort indices (CI) for each hearing protection device. These indices are defined as the linear sum of the twelve items on the questionnaire. The minimum possible CI score was 12 and the

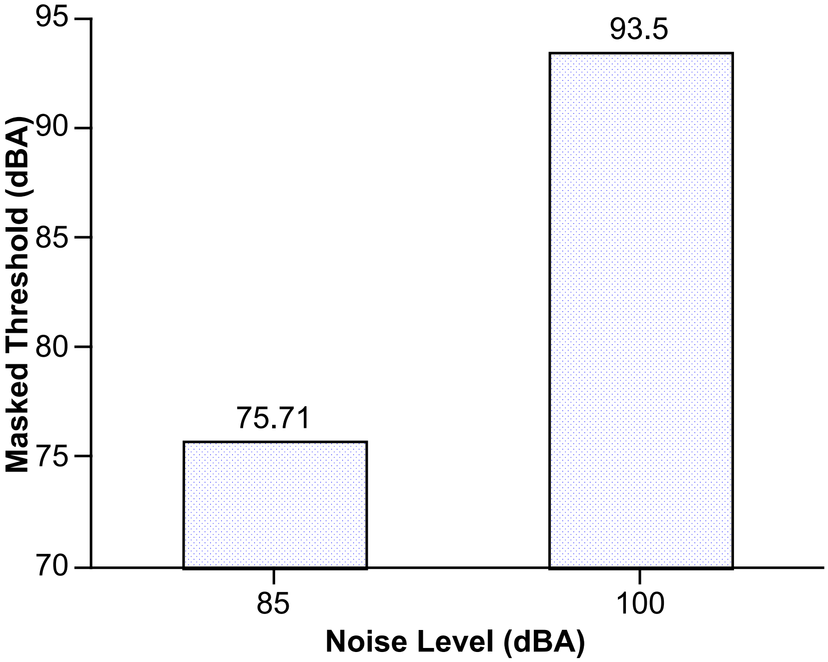


Figure 28. *Noise level main effect.*

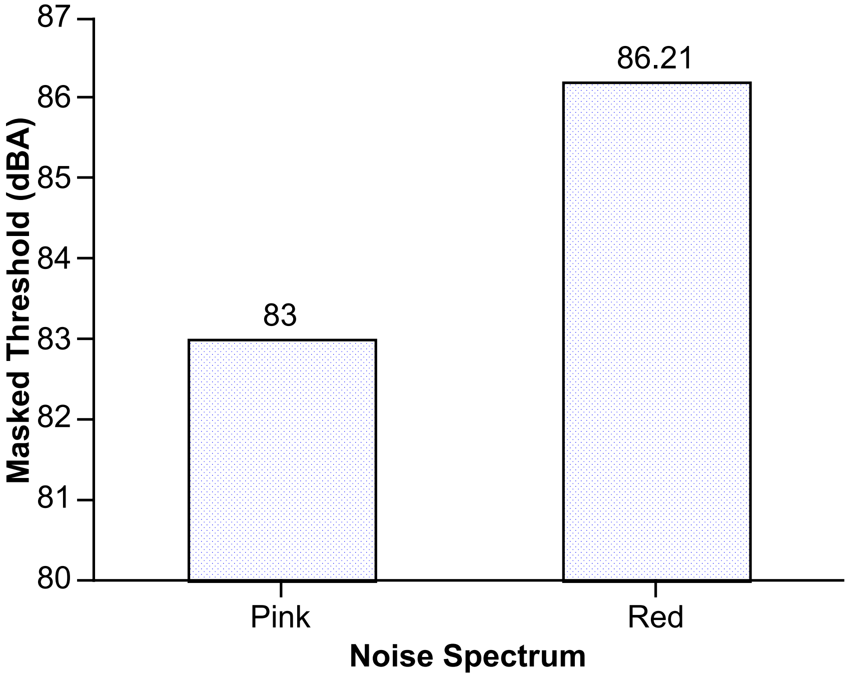


Figure 29. *Noise spectrum main effect.*

TABLE 8

ANOVA Summary Table (values in bold type indicate significance)

Source	df	MS	*F*	*p*	G-G *p*
<u>Between -Subjects</u>					
Subjects (S)	9	69.0711			
<u>Within-Subjects</u>					
Ear Condition (EC)	3	84.5963	7.91	**0.0006**	**0.0007**
EC X S	27	10.6987			
Greenhouse-Geisser Epsilon = 0.9641					
Noise Spectrum (NS)	1	163.2238	65.27	**0.0001**	
NS X S	9	2.5008			
EC X NS	3	4.8834	1.74	0.1827	0.1884
EC X NS X S	27	2.8084			
Greenhouse-Geisser Epsilon = 0.9097					

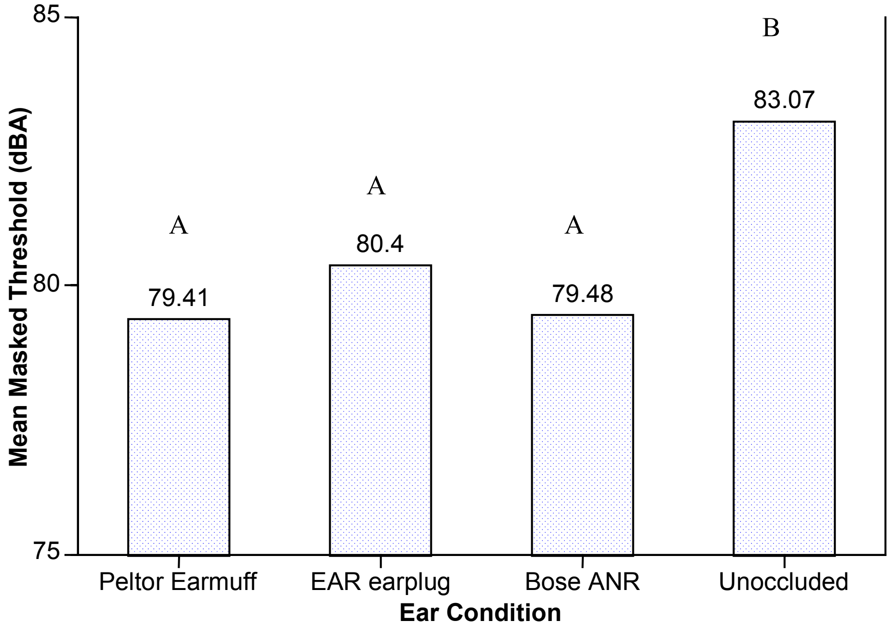


Figure 30. *Relationship between the four ear conditions used in the experiment at 85 dBA. (Means with the same letter are not significantly different,* $p \leq 0.05$*.)*

TABLE 9

Means for the Ear Conditions Used in the Experiment

Ear Condition	**Mean (dBA)**
Peltor H9A Earmuff	79.41
EAR Earplug	80.40
BOSE ANR Earmuff	79.48
Unoccluded	83.07

TABLE 10

Comfort Index Means (Standard Deviation) for Each Hearing Protection Device (Scale range: 12 to 85)

Earplug	**Passive Earmuff**	**ANR Earmuff**
55.2 (11.8)	57.0 (11.2)	55.5 (13.5)

maximum was 85 (higher scores relate to greater comfort). Table 10 summarizes the mean CI for each hearing protection device. A Friedman Rank Sum Test was performed on the CI data. This test indicated no significant difference ($p \leq 0.05$) between the three devices.

Modified Cooper-Harper Rating Scale Results

As mentioned previously, the Modified Cooper-Harper scale was used to obtain information as to the perceived mental workload of both the auditory detection and probability monitoring task. Because the Modified Cooper-Harper data is ordinal, the median response was used to obtain a general indication of the workload imposed by the probability monitoring task. Overall, subjects rated the mental workload level as unacceptable with minor but annoying difficulty.

Ranking of Hearing Protection Devices

At the end of the last experimental session, the subjects ranked the hearing protection devices based upon their perceived ability to hear the warning signal. These data were analyzed using the Friedman Rank Sum Test. The results indicated that there was no statistically significant difference ($p \leq 0.05$) between the various hearing protection devices and their perceived ability to facilitate subjects' ability to hear the auditory signal.

CHAPTER 9: DISCUSSION

BOSE ANR Earmuff vs. Peltor H9A Passive Earmuff

The BOSE ANR earmuff was expected to produce lower masked thresholds than the Peltor H9A earmuff in all noise level and type conditions. However, the results indicated that the masked thresholds were significantly lower (by about 3 dB) for the BOSE ANR earmuff only in red noise. This was probably due to the better low-frequency attenuation of the BOSE ANR earmuff compared to the passive Peltor H9A earmuff. At sound pressure levels above about 40 dB the upward spread of masking begins to occur (Deatherage, 1972). It may be that by reducing the sound pressure level of the low frequencies at the ear, the effects of upward spread of masking are reduced, allowing the subject to hear the signal better. However, the benefit of reducing the upward spread of masking was only realized in the red noise condition, which was very low-frequency biased.

The results also indicated that the masked thresholds for the BOSE ANR earmuff were lower (by about 3 dB) than the Peltor H9A in 100 dBA noise. Again, this may be due to the difference in the attenuation characteristics of the two HPDs. From the graph shown in Figure 31 it is clear that the Peltor H9A provides at least 15 dB more attenuation than the BOSE ANR earmuff in the frequency range between 1000 and 1600 Hz, which is the frequency range containing most of the warning signal's energy. The Peltor H9A earmuff attenuated both the signal and noise producing significantly higher masked thresholds.

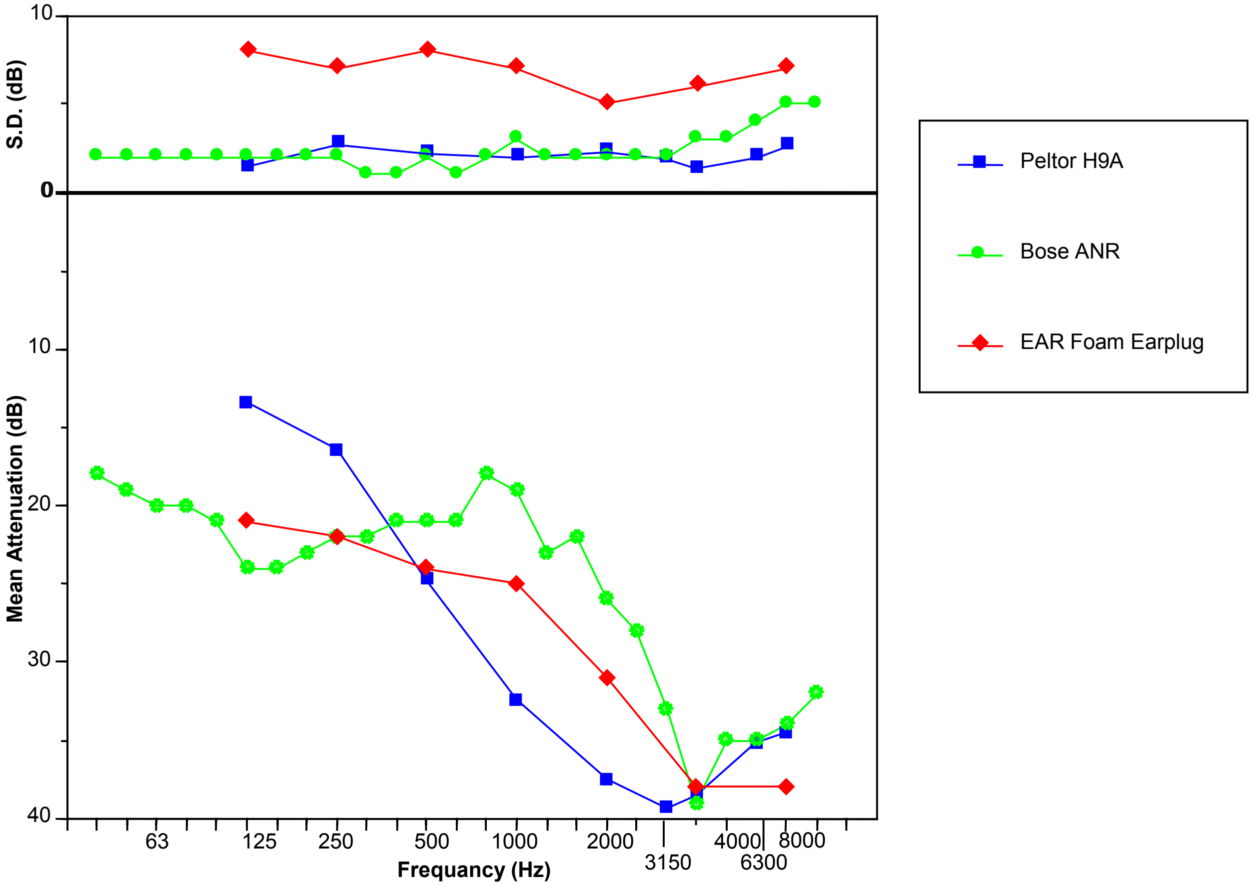


Figure 31. *Mean attenuation of the three HPDs used in the experiment (data provided by the individual HPD manufacturers).*

It was also hypothesized that the BOSE ANR earmuffs would be more comfortable (exhibit a higher CI) than the Peltor H9A. However, there was not a statistically significant difference between the two devices. From subjects' reports, this was probably due to the design of the headband on the BOSE ANR earmuff, which included a hinge at its center (at crown of the head). This hinge allows the headband to be adjusted to each wearer's head. While there is a cushion under the hinge, the hinge applied pressure to the top of the wearer's head during prolonged use. Four out of the ten subjects (two males and two females) in the experiment complained of this pressure. No one complained of discomfort associated with the other devices. Even so, the BOSE earmuff was not found to be significantly *less comfortable* than either the earmuff or earplug. One possible reason for this result might have been that the earmuff had other redeeming characteristics, such as the softer ear cups which offset this one undesirable aspect. In any case, a redesigned headband might result in a higher comfort (higher CI).

BOSE ANR Earmuff vs. EAR Foam Earplugs

Both the BOSE ANR earmuff and the EAR earplug had similar attenuation characteristics, with the earplugs providing slightly more attenuation at frequencies above 1000 Hz and the ANR earmuff providing slightly more attenuation at frequencies below 250 Hz, Figure 32. For this reason, it was difficult to predict which device would produce lower masked thresholds. The BOSE ANR earmuff exhibited no advantage over the EAR earplugs in allowing the subjects to hear the signal in either the pink noise or red noise. In fact, the results indicated that the earplug allowed the subjects to hear the signal slightly better (a 2 dB lower masked threshold) than the ANR earmuff at 100 dBA but there was no difference at 85 dBA. This may be due to the earplug providing slightly more attenuation than the ANR earmuff at the signal frequencies (about 5 dB), reducing cochlear distortion without providing excessive attenuation. It was also expected that the subjects would rate the ANR earmuff as being more comfortable than the earplug; however, as stated earlier, there was no significant difference between the devices.

EAR Earplug vs. Peltor H9A Earmuff

The Peltor H9A earmuff produced significantly higher masked thresholds (by about 5 dB) than the EAR earplug in the red noise. This was likely due to the better low-frequency attenuation of the EAR earplug as discussed previously. Subjects also were able to hear the signal better (exhibiting lower masked thresholds) while wearing the EAR earplug in 100 dBA noise. This may be due to the earplug reducing both cochlear distortion and the upward spread of masking while not excessively attenuating the signal.

Effects of HPD on Masked Thresholds

Many workers complain that if they wear hearing protection devices they will not be able to hear warning signals (Wilkins and Martin, 1987). Based upon the results of this study, that is untrue, at least for the backup alarm used in the noise spectra and levels tested. At noise levels of 85 dBA, subjects were able to hear the signal better (>3 dB difference in masked thresholds) while wearing hearing protection compared to the unoccluded condition. The primary reason for this may be the ability of hearing protection devices to reduce cochlear distortion. At high noise levels, the ear distorts the auditory stimuli, making it difficult to distinguish a signal in noise. However, HPDs reduce the sound pressure level of both the signal and noise, thus reducing cochlear distortion and allowing the subject to hear the signal better. This was an important finding because the proposed OSHA standard would require the use of hearing protectors in noise levels of 85 dBA and above (NIOSH, 1998). The proposal to change the recommended exposure level from 90 dBA to 85 dBA was made to better protect workers against *noise-induced hearing loss* (NIHL). However, an argument used by some opponents of this change is that workers will not be able to hear important warning signals if they wear HPDs at lower noise levels. They often base this opinion on a study conducted by Wilkins (1982), which found significantly higher thresholds for the occluded condition as compared to the unoccluded conditions at 75 dBC. One problem with the Wilkins study is that the warning signals used did not contrast well with the background noise. It is generally recognized that warning signals should be designed with a high level of contrast to the background noise (Deatherage, 1972; ISO, 1986).

Effects of Noise Level on Masked Thresholds

As expected, noise level was also found to affect the masked thresholds. This can be attributed to direct masking. Masking produced by the two noise spectra was related directly to the level of the noise (i.e., increasing the level of the masking noise increases the masked threshold; Hawkins and Stevens, 1950).

Effects of Noise Spectrum on Masked Thresholds

Noise spectrum was also found to significantly affect masked threshold, with red noise producing higher masked thresholds than the pink noise, by about 3 dB on average. Again, this can be attributed to the effects of masking. With higher levels of lower frequency noise, the upward spread of masking increases, requiring the signal to be presented at higher levels in order to be heard.

Mental Workload

The Modified Cooper-Harper scale was used as an indication of the mental workload imposed by both the auditory detection task and the probability monitoring task. No one indicated that the task was very easy and most rated the workload as high. This indicated that sufficient workload was placed on the subjects.

CHAPTER 10: CONCLUSION

Implication for ANR Earmuff Use

Based on the results of this study, the BOSE ANR earmuff offers no advantage over the EAR earplug, Figure 28. The ANR earmuff does show an advantage of approximately 3 dB over the Peltor H9A conventional passive earmuff in low-frequency biased noise, Figures 27 and 28. However, even with the spectrum-specific advantage over the passive earmuff, the current design of the BOSE ANR earmuff may not be appropriate for use in continuous noise environments where long wearing periods are necessary. If the design of the headband were improved, this could change.

One of the most important factors in determining the attenuation afforded by an HPD is comfort (Park and Casali, 1991). While the ANR earmuff was not rated significantly more or less comfortable than the other devices, the fact that 4 of the 10 subjects in the experiment complained of the same type of discomfort during the experiment is evidence that comfort is an issue. When HPDs are uncomfortable, workers often remove them to give their ear or head a "break." This action can result in a significant reduction of the effective protection (Casali, Lam, and Epps, 1987; Park and Casali, 1991). For example: if an HPD has a noise reduction rating (NRR) of 25, and it is removed for only 15 minutes during an 8-hour noise exposure, then its effective, or time corrected, NRR is only 20 dB or a 20% reduction in protection (Berger, 1986).

In addition to comfort issues, the BOSE ANR earmuff should be tested further to identify any benefits compared to the much cheaper earplug and conventional passive earmuff. These benefits could include better speech intelligibility, decreased masked thresholds in low-level noise (below 85 dBA), or ease of use. An ANR device may also be more appropriate for environments with intermittent noise or other situations where the HPD must be donned and doffed repeatedly.

Implications for HPD Use

Based upon the results of this study, well-fit HPDs do not appear to impair the wearer's ability to hear warning signals (at least for the backup alarm signal in the noise spectra and levels tested herein) for individuals with normal hearing. This result dispels the myth that is still prevalent in industry today, that workers will miss important auditory warnings if they wear HPDs. It is hoped that the results of this research will be added to the findings of previous research (Wilkins and Martin, 1977; Forshaw, 1977; and Abel et al., 1983) in an effort to increase the compliance of HPD usage in industry. In addition, these results can also aid in the establishment of new regulations that better protect the hearing of workers, without increasing the risk of injury due to an unheard alarm.

CHAPTER 11: FUTURE RESEARCH

Active noise reduction earmuffs are still a relatively new technology and the market for them is growing. However, continued research is necessary to ensure that they are being designed correctly. Future studies should incorporate many more subjects in the experiment to reduce the effects of subject variability. In addition, the following are suggestions for future research:

- The effects of mental workload while performing a signal detection task is still a debated issue (Wilkins and Martin, 1982). Future research should be performed to examine the effects of workload on masked thresholds (loaded and unloaded condition), in particular, looking at whether variability between subjects is reduced by increasing attentional demand (and to what extent) and how various workload levels effect masked thresholds.
- ANR earmuffs are thought to be useful in environments with unexpected intermittent noise by providing equal or better attenuation at higher frequencies compared to conventional HPDs without impairing the wearer's ability to hear signal at lower noise levels. Therefore, to include a lower noise level such as 80 dBA in the design could examine the benefits of ANR earmuffs in environments with a wider range of noise levels.
- It would also be beneficial to examine the effects of ANR earmuffs on speech intelligibility compared to other types of passive devices (earplugs and earmuffs) used in industry.
- While comfort was not found to be significantly different in this experiment, future research should examine the effects of comfort on masked thresholds. In other words, does increased comfort correlate to decreased masked thresholds for devices with similar attenuation characteristics?
- This study used one signal. Future studies should examine how HPDs differ when signals of different spectral content and temporal patterning are being listened for, including an unoccluded condition where appropriate.

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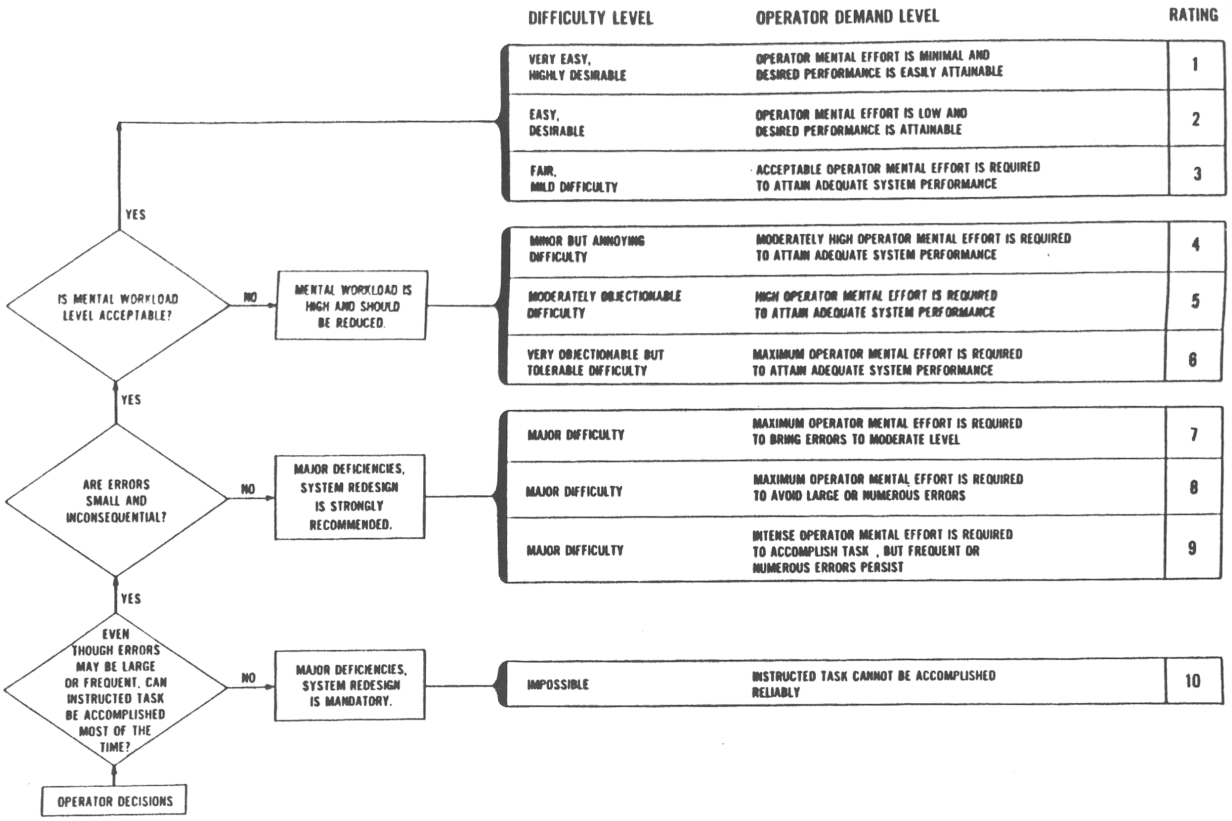
APPENDIX A

Modified Cooper-Harper Rating Form

(modified from Wierwille and Casali, 1983)



APPENDIX B

Comfort and Acceptability Rating Form

Subject:________________________ Date:__________ HPD:_____________

HOW DOES THE HEARING PROTECTOR FEEL NOW?

Uncomfortable	____:____:____:____:____:____:____	**Comfortable**
Painless	____:____:____:____:____:____:____	**Painful**
No Uncomfortable Pressure	____:____:____:____:____:____:____	**Uncomfortable Pressure**
Intolerable	____:____:____:____:____:____:____	**Tolerable**
Tight	____:____:____:____:____:____:____	**Loose**
Not Bothersome	____:____:____:____:____:____:____	**Bothersome**
Heavy	____:____:____:____:____:____:____	**Light**
Cumbersome	____:____:____:____:____:____:____	**Not Cumbersome**
Soft	____:____:____:____:____:____:____	**Hard**
Cold	____:____:____:____:____:____:____	**Hot**
Smooth	____:____:____:____:____:____:____	**Rough**
Feeling of Complete Isolation	____:____:____:____:____:____:____	**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

Informed Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING (ISE)
AUDITORY SYSTEMS LABORATORY

Informed Consent for Participants of Investigative Projects

Title of Project: Detectability of Signals in Noise While Wearing Active and Passive Hearing Protectors

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I. THE PURPOSE OF THIS RESEARCH

You are invited to participate in a research study examining issues related to the detectability of auditory signals in noise by persons wearing different types of hearing protectors and performing a simulated work task. Between 10 and 20 individuals (equally divided between males and females) are being recruited for this study with separate experimental sessions scheduled for each participant.

II. PROCEDURES

The procedures to be used in this research are as follows. First, you will be screened to determine if you qualify for the experiment. Screening will consist of a hearing test and several assessment tests. To begin with, you will be asked several questions to assess the general health and condition of your ears. Next, the experimenter will look into your ears using an otoscope to determine the condition of your ears. The hearing in both your left and right ears will then be tested with very quiet tones played through a set of headphones. You will have to be very attentive and listen carefully for these tones. **Depress the button on the hand-held switch and hold it down whenever you hear the pulsed tones and release it when you do not hear the tones.** The tones will be very faint and you will have to listen carefully to hear them. No loud or harmful sounds will be presented over the headphones. Finally, the experimenter will fit you with each of the three hearing protectors to be used in the study to ensure they fit you properly. These hearing protectors include an earplug, and earmuff, and an active noise reduction headset.

If you qualify and choose to continue, the screening session will conclude with a practice/training session of the experimental task. You will be performing two separate tasks during the experiment, a visual monitoring task and an auditory detection task. The visual monitoring task consists of one to four gauges with randomly moving pointers presented on a computer screen. Under "normal" conditions, the pointers of each gauge oscillate randomly from one end of the scale to the other, being on either side of the gauge centerline 50% of the time. At random times, however, the pointer behavior will change such that it will be on one side or the other of the gauge centerline 90% of the time. You task will be to monitor all of the gauges and indicate, using the arrow keys on the computer's keyboard, when any of the gauge pointers are behaving in this non-random fashion. For the auditory detection task, the experimenter will be presenting an auditory signal to you randomly throughout the experiment via a loudspeaker located behind you. Your task will be to indicate to the experimenter when you hear the auditory signal by pressing a response switch located on the table at which you will be seated. <u>Both tasks are of equal importance and you should perform both tasks to the best of your ability.</u>

In the training/practice session conducted at the end of the screening session, the experimenter will first demonstrate and then let you practice the visual-monitoring task by itself. When you are comfortable with this task, the experimenter will fit an earmuff on you and let you practice the auditory detection task by itself, first in quiet and then in the presence of masking noise. Once you are comfortable with performing both tasks individually, you will practice both tasks together in the presence of masking noise.

The experimental sessions will be structured in the following manner. At the beginning of each session, the experimenter will review with you the procedures for the overall session as well as for each task (the visual monitoring task as well as the auditory detection task). The experimenter will then fit the hearing protector to be used in that session on you and ensure a proper fit for the device. You will then be seated at a table on which the computer controlling the visual monitoring task and the auditory response switch sit. The visual monitoring task will then be initiated followed by initiation of the masking noise. Soon thereafter, the experimenter will begin presenting the auditory signal for which you will be listening. (During the experimental trials, the experimenter will be seated outside your field of view, but she will be able to see you and will be monitoring you throughout the session.) After a sufficient number of auditory detection trials have been completed, the experimental tasks will be terminated and you will be asked to take a break while the experimenter prepares the equipment for the next noise type/level combination. (<u>Please do not remove or adjust the hearing protector during these breaks. It is important that the fit of the hearing protector be consistent across all trials conducted during a single session.</u>) All of the noise type/level combinations (four trials – two noise types at two levels each) for a specific hearing protector will be conducted during a single experimental session lasting about two hours. This will be done to prevent hearing protector fit from confounding the results. The exception to this will be the unoccluded trials (conducted only at 85 dBA) which will be conducted in separate sessions (lasting one hour or less) on separate days.

A total of five experimental sessions will be conducted, two sessions in which you will not be wearing a hearing protector (the unoccluded conditions) and three sessions in which you will be wearing a hearing protector (the occluded conditions). In the sessions in which you will be unoccluded (not wearing a hearing protector), the background noise will be presented **only** at

85 dBA. (OSHA regulations allow occupational exposure to continuous noise at levels of 90 dBA for 8-hours per 24-hour workday without requiring the use of hearing protection devices. You will be exposed only to levels of 85 dBA when not wearing hearing protectors and then only for two one-hour periods scheduled on different days. In all other conditions, you will be wearing hearing protectors which will reduce the noise levels reaching your ears to levels below 85 dBA. The noise exposures received by you while participating in this study are not sufficient to cause any damage to your hearing.) In the sessions in which you will be wearing hearing protectors, two background noise levels will be used, 85 dBA and 100 dBA.

In addition to the formal experiment outlined above, three types of subjective preference data will also be collected as part of the study. At the end of each experimental session, you will be asked to complete a questionnaire intended to determine the perceived comfort of the hearing protector worn during the session. You will also be asked to fill out a subjective workload rating scale intended to quantify the workload imposed by the visual-monitoring task. Finally, at the end of the last experimental session, you will be asked to rate the three hearing protectors used in the study in terms of which devices best enabled you to hear the auditory signal.

III. RISKS

The Occupational Safety and Health Administration (OSHA) allows industrial workers in the U.S. to be exposed to continuous 100 dBA noise for two hours every day without wearing hearing protectors and to levels of 85 dBA for periods exceeding eight hours each day. Your maximum exposure to 85 dBA noise while not wearing hearing protectors will be for two one-hour periods scheduled on different days. In all other conditions, for both the 85 dBA and 100 dBA noise levels, you will be wearing hearing protection which will reduce the loudest levels reaching your ears to 85 dBA or below. **The noise exposures received by you while participating in this study are not sufficient to cause any damage to your hearing. There is no risk to your well-being posed by this study.**

The hearing protectors used in this study will be fit by the experimenter. Hearing protectors are intended to provide a snug fit so that noise will be blocked. Therefore, they may seem tight in or around your ears. Some minor discomfort may result from the tight fit, but the protectors will not harm you in any way.

IV. BENEFITS OF THIS RESEARCH

Your participation in this experiment will provide information that will give researchers insight into the issues relating to the detection of auditory signal in noise by individuals wearing hearing protectors while performing their jobs.

No guarantee of benefits has been made to encourage you to participate. You may receive a summary of the results of this research when completed. If you desire to receive such a summary, please give or send a self-addressed envelope to the experimenter. To avoid biasing other potential participants, you are requested not to discuss the study with anyone until six months from now.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. At no time will the researchers release the results of the study to anyone other than the individuals working on the project without your written consent. The information you provide will have your name removed and only a participant number will identify you during analyses and any written reports resulting from this research.

VI. COMPENSATION

For participation in this experiment, you will receive $8.00 for each hour that you participate.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time without penalty. If you choose to withdraw, you will be compensated for the portion of time you have spent in the study. There may also be certain circumstances under which the investigator may determine that you should not continue as a participant in this project. These include, but are not limited to, unforeseen health-related difficulties, inability to perform the task, and unforeseen danger to yourself, the experimenter, or the equipment.

VIII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for projects involving human participants at Virginia Polytechnic Institute and State University, and by the Department of Industrial and Systems Engineering.

IX. PARTICIPANT'S RESPONSIBILITIES

I know of no reason why I cannot participate in this study. I have the following responsibilities:

- To listen attentively to the sounds during the screening and experimental sessions as well as follow instructions and perform the experimental tasks to the best of my ability.
- To notify the experimenter at any time about discomfort or desire to discontinue participation.

____

Signature of Participant

X. PARTICIPANT'S PERMISSION

Before you sign this form, please make sure that you understand, to your complete satisfaction, the nature of the study and your rights as a participant. If you have any questions, please ask the experimenter at this time. If you decide to participate, please sign below.

I have read a description of this study and understand the nature of the research and my rights as a participant. I hereby consent to participate, with the understanding that I may discontinue participation at any time if I choose to do so, being paid only for the portion of the time that I spend in the study.

Signature ________________________________
Printed Name ________________________________
Date ________________________________

The research team for this experiment includes Dr. John G. Casali, Director of the Auditory Systems Laboratory, Dr. Gary S. Robinson, Senior Research Associate, and Erika Christian, Graduate Research Assistant. They may be contacted at the following address and phone numbers:

Auditory Systems Laboratory
Room 538 Whittemore Hall
Virginia Tech
Blacksburg, VA 24061
Dr. Casali: (540) 231-9081
Dr. Robinson: (540) 231-2680
Erika Christian: (540) 231-9086

In addition, if you have detailed questions regarding your rights as a participant in University research, you may contact the following individual:

Mr. Tom Hurd
Director of Sponsored Programs
301 Burruss Hall
Virginia Tech
Blacksburg, VA 24061
(540) 231-5281

APPENDIX D

Participant Screening Forms

Pure-Tone Audiometric Tests for Normal Hearing

Participant: ________________________________ Age:_____ Sex:_____

Phone:____________________ Screening Date:_________ Qualify?____

Right Ear

Frequency Hz	t-1	t-2	t-3	t-4	t-5	t-6	final threshold
125	_____	_____	_____	_____	_____	_____	_____
250	_____	_____	_____	_____	_____	_____	_____
500	_____	_____	_____	_____	_____	_____	_____
1000	_____	_____	_____	_____	_____	_____	_____
2000	_____	_____	_____	_____	_____	_____	_____
3000	_____	_____	_____	_____	_____	_____	_____
4000	_____	_____	_____	_____	_____	_____	_____
6000	_____	_____	_____	_____	_____	_____	_____
8000	_____	_____	_____	_____	_____	_____	_____

Left Ear

Frequency Hz	t-1	t-2	t-3	t-4	t-5	t-6	final threshold
125	_____	_____	_____	_____	_____	_____	_____
250	_____	_____	_____	_____	_____	_____	_____
500	_____	_____	_____	_____	_____	_____	_____
1000	_____	_____	_____	_____	_____	_____	_____
2000	_____	_____	_____	_____	_____	_____	_____
3000	_____	_____	_____	_____	_____	_____	_____
4000	_____	_____	_____	_____	_____	_____	_____
6000	_____	_____	_____	_____	_____	_____	_____
8000	_____	_____	_____	_____	_____	_____	_____

SCREENING FORM

Otoscopic Data

Occluding wax?: ____________________

Ear canal irritation?: ____________________

Unusual canal characteristics: ____________________

Eardrum perforations?: ____________________

Eardrum scar tissue? ____________________

Foreign matter?: ____________________

Self-Report Data

Tinnitus or head noises: ____________________

Otopathological history: ____________________

Occupation: ____________________

Noisy hobbies: ____________________

HPD experience: ____________________

Other: ____________________

VITA

ERIKA CHRISTIAN

Erika Christian was born and raised in Virginia. She earned her B.S. in Industrial and Systems Engineering from Virginia Polytechnic Institute and State University in 1997. As an undergraduate, Erika served as a research assistant in the Auditory Systems Laboratory in the area of Intelligent Vehicle Highway Systems (IVHS). Upon completion of her Bachelor's, Erika continued studies at Virginia Polytechnic Institute and State University with a concentration in the area of Human Factors Engineering. During this time, Erika conducted the research outlined in this thesis. She also participated in other projects including IVHS and Human Computer Interaction. Erika is an active member of the Human Factors and Ergonomics Society as well as the National Society of Black Engineers.