AZIMUTHAL LOCALIZATION AND DETECTION OF VEHICULARBackup ALARMS
UNDER ELECTRONIC AND NON-ELECTRONIC HEARING PROTECTION DEVICES
IN NOISY AND QUIET ENVIRONMENTS

by

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Keywords: Hearing protector, electronic earmuff, musician's earplug, flat attenuation, backup alarm, reverse alarm, alarm spectrum, sound localization, auditory warning signal localization, detection distance, broadband backup alarm, Combat Arms earplug
Objective assessment for the effect of hearing protectors, background noise levels, and backup alarm acoustic features on listeners’ abilities to localize backup alarm signals in the horizontal dimension, as well as on their ability to detect backup alarm signals in the distance dimension, is lacking in the acoustics and safety literature. Accordingly, two research experiments were conducted for this dissertation.

In the first experiment, the effect of seven hearing protectors, two background pink noise levels (60 dBA and 90 dBA), and two backup alarm signals (standard and spectrally-modified) on the ability of normal hearing listeners to localize backup alarm signals in the horizontal dimension was investigated. Results indicated that a diotic sound transmission earmuff significantly degraded localization accuracy as compared to all other hearing protectors and the open ear condition. In addition, no significant difference existed between the open ear condition and the other hearing protectors in localization accuracy in most of the conditions tested. However, the E-A-R/3M HiFi™ earplug was advantageous in localization performance since it provided a significantly higher percentage correct localization than the Moldex foam earplug, the diotic earmuff, and the dichotic earmuff in 90 dBA pink noise. As for main effects of the other independent variables, the 90 dBA pink noise significantly degraded localization performance as compared to the quiet condition of 60 dBA, and a spectrally-modified backup alarm significantly improved localization performance as compared to the
standard (narrowband) backup alarm. Potential application of these results includes the revision of backup alarm standards. In addition, these results provide clear advice for safety professionals to avoid the application of diotic sound transmission earmuffs for workers if localizing backup alarms is important.

In the first experiment, listeners’ feeling of comfort for each hearing protector was assessed subjectively by using a comfort rating scale. In addition, a subjective assessment for listeners’ confidence in their localization decisions was established. Results indicated no significant difference between the hearing protectors in terms of comfort. However, in terms of listeners’ confidence in localization decisions, their confidence was significantly degraded when they were fitted with the diotic earmuff. By contrast, they showed significantly more confidence in their localization decisions when they were fitted with the E-A-R/3M HiFi\textsuperscript{TM} earplug as compared to when they were fitted with the Moldex foam earplug, the E-A-R/3M Ultrafit\textsuperscript{TM} earplug, and the Bilsom passive earmuff.

In the second experiment, listeners’ performance in detecting a stationary backup alarm signal, including both a standard (narrowband) and broadband (pulsed white noise) alarm, was determined while they were equipped with various passive and electronic hearing protection devices. Listeners’ performance was quantified by detection distance, which was defined as the distance between the stationary backup alarm device and the position where the listener detected the backup alarm signal. The resultant data demonstrated that normal hearing listeners detected a standard (narrowband) backup alarm signal at significantly longer distances as compared to the broadband (Brigade\textsuperscript{TM}) backup alarm signal, thus indicating the earlier forewarning by
the standard alarm. In addition, passive hearing protection devices characterized with high attenuation significantly reduced the detection distance. These results may be applied to assist safety professionals in selecting hearing protectors and backup alarm signals that provide on-foot workers with ample time to react to an approaching backing vehicle, thus improving their safety.
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INTRODUCTION

Annually, around 30 million workers, including construction workers, in the United States are at risk of developing noise-induced hearing loss (NIHL) (Occupational Safety & Health Administration [OSHAa], 2007). Hearing protection devices (HPDs) are used widely to protect workers from NIHL due to their practical and economical advantages (Berger, 2003). However, this HPDs benefit is obscured by the often complaints from workers about their negative effect on comfort (Casali & Grenell, 1990), signal detection (Wilkins & Martin, 1987), and signal localization (Atherley & Noble, 1970). The importance of detecting and localizing auditory warning signals is demonstrated by the fatality statistics from the road construction industry. During a six-year period beginning in 1992, 154 on-foot workers were fatally injured by being struck by construction vehicles in highway/street work zones. Among those incidents, around 51% were caused by backing construction vehicles (Pratt, Fosbroke, & Marsh, 2001). In their report, Pratt et al. presented some of the cases involved backing accidents in construction sites. In some of these cases the backup alarm was reported to be sounding during the time of the accident. Therefore, it must be assumed it was undetected, non-localizable, and/or unheeded. Among Pratt et al. recommendations for many of these accident cases, is to install an audible backup alarms on construction vehicles. Knowing that construction workers are exposed to high levels of noise (Suter, 2002), it is quite possible that the previous accidents were caused by workers’ inability to detect and/or localize backup alarm signals.
In addition to being able to detect auditory warning signals, it is crucial to localize them. Although humans rely heavily on their visual system to localize objects in their surroundings (Blauert, 1997), this reliance is shifted towards their auditory system at certain circumstances. For example, when workers’ vision is cluttered (e.g., by fog, dust, wearing a welding mask, etc), they need to rely on their hearing to localize auditory warning signals. There is no specific Bureau of Labor Statistics (BLS) or other data showing the number of accidents caused by poor awareness of the location of reversing vehicles in the construction workers’ vicinity. Even so, such misjudgment of the location of these vehicles by construction workers is one of the factors that contribute to workers being struck by reversing vehicles, as evidenced by the large amount of litigation and workers compensation claims which relate to backup alarms (J. Casali, personal communication, Jan, 2007).

The backup alarm signal is arguably the most common auditory warning signal in construction sites. In the research literature, most of the effort has been directed toward the effect of hearing protectors on the detection of backup alarm signals (Casali, Robinson, Dabney, & Gauger, 2004; Lovejoy, 2008). By the time of this writing, no study was available in the literature that investigated the effect of hearing protectors on localizing backup alarms. With the above in mind, the proposed research focused upon the individual worker’s ability to localize a standard construction vehicle backup alarm, as influenced by the type of hearing protector worn and the ambient noise which surrounds the listening situation. In an effort to enhance localization ability, a redesigned backup alarm was also investigated and compared against the standard
alarm. In addition, individuals’ ability to detect construction vehicle backup alarm across the distance as influenced by the type of hearing protector worn was investigated.
NOISE EXPOSURE IN CONSTRUCTION INDUSTRY

Noise is considered as one of the major occupational health hazards. Exposures to hazardous levels of noise may lead to noise-induced hearing loss (NIHL), acoustic trauma (e.g., permanent damage to the ear due to exposure to impulsive sounds), tinnitus, or hyperacusis (Casali, 2006). Background noise in the construction industry is usually characterized by being intermittent and outdoor. However, it becomes continuous when construction workers use powered equipment especially vehicles (Suter, 2002). Around half million construction workers are estimated to be exposed to hazardous noise levels (Simpson & Bruce, 1981). This number is probably higher today than in the 80’s due to the increment in the construction workforce. To protect construction workers from the detrimental effect of noise exposure, government noise regulations pertaining to construction industry were promulgated and enforced by the Occupational Safety and Health Administration (OSHA). An overview of these regulations and the noise exposure levels of construction workers are provided below.

Noise Regulations for Construction Industry in the United States

In 1970, the United States Department of Labor legislated the Occupational Safety and Health Act, which enforced protecting workers from workplace hazards, including noise (Suter, 2003). In the United States, there are two regulations for noise exposure in construction industry, OSHA (1926.52) and OSHA (1926.101) (Suter, 2002). OSHA (1926.52) mandates the use of protective measures against noise when its levels exceed those presented in Table 1. Administrative and engineering controls in addition to hearing protectors are described by this regulation as a protective measure. If the administrative and engineering controls fail to protect workers from hazardous
noise levels, then the use of hearing protectors becomes mandatory as stated by OSHA (1926.101).

Table 1.
*OSHA’s permissible noise exposures for the construction industry (OSHAb, 2000).*

<table>
<thead>
<tr>
<th>Duration per day, hours</th>
<th>Sound level dBA, slow response</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>92</td>
</tr>
<tr>
<td>4</td>
<td>95</td>
</tr>
<tr>
<td>3</td>
<td>97</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>1½</td>
<td>102</td>
</tr>
<tr>
<td>1</td>
<td>105</td>
</tr>
<tr>
<td>½</td>
<td>110</td>
</tr>
<tr>
<td>¼ or less</td>
<td>115</td>
</tr>
</tbody>
</table>

**Noise Exposure Levels in Construction Industry**

In 2004, Seixas & Neitzel reported the results of their five-year prospective study which was started to find the noise exposure levels for 393 novice construction workers. These workers wore dosimeters to measure their noise exposure levels for a total of 730 full workshifts. The measurements represented the noise exposure levels at each minute of the workshift in addition to a time-weighted average (TWA) noise exposure level for the total workshift. These measurements were captured according to the National Institute for Occupational Safety & Health (NIOSH) occupational noise exposure guideline (NIOSH, 1998). Based on this guideline, an 8-hour TWA noise exposure above a recommended exposure level (REL) of 85 dBA is hazardous. Obviously, the NIOSH REL is more stringent than OSHA permissible exposure limit (PEL) of 90 dBA for 8 hours (see Table 1). Seixas & Neitzel reported that ironworkers, laborers, carpenters, masons, operating engineers, cement masons, electricians, and
sheet metal workers were exposed to 8-hour equivalent time-weighted average noise levels above 85 dBA (Figure 1). In addition, more than 50% of their measurements were above 85 dBA for each of the aforementioned by-trade construction workers (Figure 2). They also provided the average noise levels measured for different types of construction equipment (Table 2). Apparently, all of these equipment produced noise levels above the NIOSH REL (i.e., 85 dBA TWA) and many of them produced noise levels above the OSHA PEL (i.e., 90 dBA TWA).

*Figure 1. Noise exposure levels for construction workers by job or trade (Used with permission of Seixas & Neitzel, 2004).*
Figure 2. Percentage of noise exposures above 85 dBA TWA by job or trade (Used with permission of Seixas & Neitzel, 2004).

Table 2.
Average noise level for a sample of construction equipment (Used with permission of Seixas & Neitzel, 2004).

<table>
<thead>
<tr>
<th>Tool</th>
<th>Average noise level for each tool event (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grader</td>
<td>86.4</td>
</tr>
<tr>
<td>Compactor, roller</td>
<td>88.2</td>
</tr>
<tr>
<td>Backhoe</td>
<td>89.3</td>
</tr>
<tr>
<td>Forklift</td>
<td>89.4</td>
</tr>
<tr>
<td>Excavator</td>
<td>90.0</td>
</tr>
<tr>
<td>Loader</td>
<td>93.0</td>
</tr>
<tr>
<td>Bulldozer</td>
<td>100.2</td>
</tr>
<tr>
<td>Hand power saw</td>
<td>96.6</td>
</tr>
<tr>
<td>Rotohammer</td>
<td>95.1</td>
</tr>
</tbody>
</table>

In 2008, Casali & Lancaster conducted in-field noise measurements for approximately 50 types of construction equipment. Their results indicated that many pieces of construction equipment, including vehicles and power tools, produced an A-weighted equivalent-continuous noise level ($L_{eq}$) above the Recommended Exposure Limit (REL) recommended by NIOSH, which is 85 dBA time-weighted average (TWA) using a 3 dB as time exchange rate. And some had $L_{eq}$ values above the Permissible
Exposure Limit (PEL) promulgated by OSHA which is 90 dBA TWA using a 5 dB as time exchange rate (see Figure 3). They also estimated the noise exposure for construction workers along their 8-hour workshift by conducting dosimetry measurements, for representative partial shifts. Their results again showed that noise exposure levels were higher than the NIOSH REL (i.e., 85 dBA TWA) for many construction workers and some of them were exposed to noise levels above the OSHA PEL of 90 dBA TWA (Figure 4).

Figure 3. Noise levels for different construction equipment (Used with permission of Casali & Lancaster, 2008).
Obviously, the results of the aforementioned two studies provided clear evidence that construction workers are exposed to hazardous levels of noise. In addition to its detrimental effect on workers’ hearing, exposure to high levels of noise may mask auditory warning signals or deteriorate workers’ ability to localize them. Since the interest in this research was to investigate listeners’ ability to localize backup alarms installed on construction vehicles, including background noise levels that are commonly existed in construction sites as one of the independent variables in this research was believed to provide more applicable and valid results.

Figure 4. Noise exposures in TWA and Maximum levels during measurement period for different construction vehicles along an 8-hour workshift (Used with permission of Casali & Lancaster, 2008).
Due to their design, many construction vehicles and mobile equipment (e.g., backhoes, loaders, excavators, dump trucks, etc) have an obstructed rear view which makes it difficult for drivers to view the area behind their vehicles to insure it is free of on-foot workers. For this reason, backup (i.e., reverse) alarms are used to warn on-foot workers of the danger imposed by backing construction vehicles and mobile equipment. The use of these alarms is common in general industry as well as in construction and has been since the 1970’s. In 2008, Casali & Lancaster interviewed many subject matter experts, including construction site supervisors, construction workers and vehicle operators, and construction engineers and the interviews’ outputs indicated that backup alarm is the prevalent and most ubiquitous auditory warning in construction sites (see Table 3).

Table 3. 
*Types of auditory signals/alarms associated with different construction vehicles and mobile equipment (Used with permission of Casali & Lancaster, 2008).*

<table>
<thead>
<tr>
<th>Equipment Type/Operation</th>
<th>Signal or Alarm</th>
<th>Purpose of Signal or Alarm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Grader</td>
<td>Alarm</td>
<td>Backup</td>
</tr>
<tr>
<td>Air Compressor</td>
<td>Alarm</td>
<td>Low Pressure Warning</td>
</tr>
<tr>
<td>Milling Machine</td>
<td>Alarm</td>
<td>Backup</td>
</tr>
<tr>
<td>Crane</td>
<td>Alarm</td>
<td>Overload, Backup, Load Lowering</td>
</tr>
<tr>
<td>Crawler Loader</td>
<td>Alarm</td>
<td>Backup</td>
</tr>
<tr>
<td>Dozer</td>
<td>Alarm</td>
<td>Backup</td>
</tr>
<tr>
<td>Excavator</td>
<td>Both</td>
<td>Backup, Movement, Off-balance</td>
</tr>
<tr>
<td>Forklift</td>
<td>Alarm</td>
<td>Backup, Load Lowering</td>
</tr>
<tr>
<td>Loader Backhoe (Wheeled)</td>
<td>Both</td>
<td>Backup, Horn, Movement</td>
</tr>
<tr>
<td>Scraper</td>
<td>Alarm</td>
<td>Backup</td>
</tr>
<tr>
<td>Skid Steer Compact Loader ('Bobcat')</td>
<td>Both</td>
<td>Backup, Off-balance</td>
</tr>
<tr>
<td>Trencher/Boring Machine/Cable Plow</td>
<td>Alarm</td>
<td>Backup</td>
</tr>
<tr>
<td>Dump Truck</td>
<td>Both</td>
<td>Backup, Horn, Turning</td>
</tr>
<tr>
<td>Water Pump Equipment</td>
<td>Alarm</td>
<td>Pressure Irregularity</td>
</tr>
<tr>
<td>Wheel Loader</td>
<td>Both</td>
<td>Backup, Turning, Brake Engage</td>
</tr>
<tr>
<td>Roller</td>
<td>Alarm</td>
<td>Backup</td>
</tr>
</tbody>
</table>
Backup Alarms’ Regulations and Standards in the United States

OSHA has two regulations that have bearing on the use of backup alarms on construction motor vehicles and moving machines. For motor vehicles, OSHA regulations (OSHAc, 2000) state, “No employer shall use any motor vehicle equipment having an obstructed view to the rear unless: (b)(4)(i) The vehicle has a reverse signal alarm audible above the surrounding noise level or: (b)(4)(ii) The vehicle is backed up only when an observer signals that it is safe to do so” (Part 1926.601[b][4]). Also, for moving machines, OSHA regulations (OSHAd, 2000) state, “No employer shall permit earthmoving or compacting equipment which has an obstructed view to the rear to be used in reverse gear unless the equipment has in operation a reverse signal alarm distinguishable from the surrounding noise level or an employee signals that it is safe to do so” (Part 1926.602[a][9]). Despite OSHA’s backup alarms regulations, fatalities from backing accidents occur with alarming frequency. Purswell & Purswell (2001) investigated OSHA accident reports, looking for backing accidents. They found that approximately 43% of the investigated backing accidents occurred while the backup alarm was operable. Apparently, this statistic makes the effectiveness of commercial backup alarms questionable, in terms of whether the backup alarms were inaudible, not localizable, or not heeded.

The acoustical properties of the backup alarm signal are specified by the standards of the Society of Automotive Engineers (SAE). Based on the backup alarm’s intensity, where it is required to be measured four feet away from the alarm device in a free field, the SAE standard J994b-2009 specifies six types of backup alarms, as follows:
• Type A - 112 dBA
• Type B - 107 dBA
• Type C - 97 dBA
• Type D - 87 dBA
• Type E - 77 dBA
• Type F - Other

The SAE standard J994b-2009 also specifies the nature of the frequency spectrum for the backup alarm signal. The dominant frequencies of the backup alarm signal must fall between 700 Hz and 2800 Hz.

**Design of Warnings and the Backup Alarm Signal**

The purpose of warnings, including auditory ones, is to avoid accidents by providing safety-related information (Wogalter, 2006a). To accomplish this successfully, the warning should have attention-call features. In addition, it should be as informative as possible about the existing hazards. The interaction between humans (i.e., warnings’ information receivers) and warnings’ information started through their senses or information receiving channels as depicted in Figure 5. At this stage, the quality of humans’ senses (e.g., normal hearing) has a great impact on their final reactions. Warnings’ information then recognized (i.e., given meaning) through the stage of comprehension, after being attended to through the stages of attention switch and attention maintenance. And finally, lead to human reaction at the behavior stage.

As a type of warning signal, backup alarms are designed to communicate information about the possibility of being struck by backing vehicles. According to the
above description of warnings’ design features, backup alarms should call construction
workers attention as well as provide them with accurate information about the extant
hazard. By mandating installing only audible backup alarms on construction vehicles,
OSHA regulations essentially key on the attention-call feature for backup alarms while
arguably ignoring the informative one. In other words, by following the OSHA
regulations, the backup alarm signal may indeed be detected, by gaining access
through the hearing sense, but misperceived (e.g., misrecognized, not localized, etc)
due to lack of information. For construction workers who are exposed to backing
vehicles, it is not enough to simply detect the backup alarm signals they must also
perceive the signal’s direction and distance to be able to evade the backing vehicle and
avoid injury (Figure 6). A field study conducted by Withington in 2004 showed that
around 90% of the participants believed that it is important to know which of the
surrounding vehicles was approaching them. In essence, it is cardinal to design a
backup alarm system that is both detectable and localizable. Discussions on how to
foster localizing backup alarms will be provided in later chapters.

Another flaw in the design of backup alarm systems is the high rate of false
alarms (attending to the backup alarm signal although it conveys no hazardous
information) associated with them, which can lead to decreased vigilance from the
intended on-foot workers. This high rate of false alarms results from the fact that the
backup alarm signal starts beeping automatically when the vehicle or moving equipment
is shifted into reverse, whether or not it actually moved in reverse regardless of whether
or not it imposes a danger to the on-foot workers (Duchon & Laage, 1986).
The prevalence of backup alarms in construction industry and the aforementioned flaws in their design necessitated testing the effectiveness of the standard backup alarm in terms of localization as was the purpose of the research herein.

**Figure 5.** Communication-human information processing (C-HIP) model (Used with permission of Wogalter, 2006b). Permission also granted by Taylor & Francis Group.

**Figure 6.** Human tasks involved when interacting with backup alarms (Used with permission of Casali & Alali, 2009).
HEARING PROTECTION DEVICES

Hearing protection devices (HPDs) are a type of personal protective equipment (PPE) that is used to protect workers from occupational noise. It is considered as a last resort if other interventions (e.g., engineering or administrative controls) to alleviate noise exposure are economically and practically infeasible. HPDs can be classified into earplugs, earmuffs, or helmets (Berger, 2003). A detailed description for each one is provided below.

Types of Hearing Protection Devices

**Earplugs.** Earplugs are used to mitigate the transmission of environmental sounds to the eardrum by providing a seal around the earcanal (Figure 7). Earplugs can be classified into five groups: foam earplugs, premolded earplugs, formable earplugs, custom-molded earplugs, and semi-insert earplugs (see Figure 8) (Berger, 2003).

![Figure 7. Acoustic seal provided by earplugs (Used with permission of Berger, 2003). Permission also granted by the American Industrial Hygiene Association.](image-url)
Based on the material from which they are manufactured, foam earplugs (sometimes called “roll-down” foam earplugs) can be classified as slow-recovery polyvinyl chloride (PVC) or polyurethane (PU) earplugs. The PVC foam earplugs are typically formed in a cylindrical (see Figure 8a) or hexagonal shape with a diameter of about 14 mm and a length range of 18 - 23 mm. On the other hand, the PU foam earplugs are typically formed either as a bullet or a bell (see Figure 8a). Even though the PVC and PU foam earplugs have approximately the same attenuation characteristics, PVC earplugs are preferred since they provide more comfort. In addition, their use in humid environments is superior over the PU earplugs since they
are less absorptive to moisture thus providing better recovery to their original shape from their roll-down shape. The use of foam earplugs is common in many industries due to their high attenuation characteristics and to the amount of comfort they provide. However, their use becomes questionable if workers’ hands are exposed to dirt, dust, or small-sharp materials since they may transfer to workers’ ears after the earplug insertion (Berger, 2003).

As shown in Figure 8b, premolded earplugs, which are made from flexible materials such as foam, polyvinyl chlorides, and silicon, consist of a stem and flanges or a hemispherical dome that is attached to the stem. These earplugs are advantageous over the foam earplugs since they can be inserted to the earcanal without any roll-down action by workers’ dirty hands (i.e., premolded earplugs provide a hygienic advantage). However, the acoustic seal provided by this type of earplugs is not as effective as the one provided by the foam earplugs (Berger, 2003).

The third type of earplugs is the formable earplug (Figure 8c). Usually, they are made from cotton/wax combinations, silicon putty, or spun fiberglass. Even though these earplugs are popular in customer markets, they are rarely used in industry due to their poor sealing performance as compared to foam or premolded earplugs (Berger, 2003).

Unlike the previous types of earplugs that came in different shapes and sizes to fit the largest segment of the population possible, custom-molded earplugs are manufactured for a particular individual’s use. The custom-molded earplugs (Figure 8d) are manufactured after taking an impression of the earcanal. They are usually manufactured from silicon putties, but sometimes they can be manufactured from vinyl
or acrylics. Most of these earplugs have a part which goes inside the ear canal to provide an acoustic seal and another part which covers some portions of the concha and the pinna to keep the earplug in position. Compared to other earplugs, the custom-molded earplugs can be easily inserted into the ear canal with fewer fitting instructions. However, the amount of attenuation provided by the custom-molded earplugs is less than those provided by other earplugs. In addition, manufacturing custom-molded earplugs is a time-consuming process, which may lead to administrative problems if the worker loses his/her earplug (Berger, 2003).

The fifth and last type of earplugs is the semi-insert earplug. As shown in Figure 8e, the semi-insert earplug consists of a band that holds two plugs and applies a spring-force to keep them inside the ear canal. The two plugs can be manufactured from vinyl, silicone, or PU foam and formed in a bullet, conical, or flanged shape. Semi-insert earplugs can be used in environments where intermittent noise is dominant since they can be placed and removed easily. However, the spring-force applied by the band may cause a comfort problem if these earplugs are used for long periods of time (Berger, 2003).

**Earmuffs.** Earmuffs consist of three main parts: earcup, headband (or sometimes an arm for hardhat attachment), and cushion (see Figure 9). The outer side of the earcup is usually manufactured from plastic, while the inside part is usually covered with an open-cell foam to prevent the transmission of high frequency (greater than 2 kHz) sounds to the eardrum. Headbands, which are made from metal or plastic, are used to hold the earcups on the ears by applying a spring force, thus providing an acoustic seal around the head bone with the assistance of the cushions, which are
usually filled with foam or fluid (Figure 10). Earmuffs are usually manufactured in one size to fit as large a segment of the population as possible (Berger, 2003).

**Figure 9.** Earmuffs’ design (Used with permission of Berger, 2003). Permission also granted by the American Industrial Hygiene Association.

**Figure 10.** Acoustic seal provided by earmuffs (Used with permission of Berger, 2003). Permission also granted by the American Industrial Hygiene Association.

The efficiency of earmuffs can be affected by many factors, such as earcup volume and mass, headband force, earcup opening area, and the earmuff materials.
Large-volume earcups have more sound attenuation capability in the 125 - 1000 Hz frequency range, while small- and medium-volume earcups are more effective in attenuating high-frequency sounds (above 2 kHz). The headband force is very important since it is intended to insure a full attachment of the cushions to the user’s head to provide an optimum seal. Although high-headband forces are preferred to provide this optimal seal, this may be at the expense of the users’ comfort. This causes a dilemma for earmuff manufacturers, and they constantly strive to find the optimum combination of headband force and user comfort. Regarding the earcup opening area, the attenuation of the earmuff increases as this area is decreased. But again, this attenuation benefit comes at the expense of the earmuff user’s comfort: it will compromise the ability to contain the pinna inside small earcup opening areas. Finally, different cushion materials provide different attenuation characteristics at different frequency ranges. Fluid-filled cushions attenuate much better at low frequencies, while foam cushions attenuate better at high frequencies (Berger, 2003).

Earmuffs can be used practically in environments with intermittent noise since they can be donned and doffed easily. On the other hand, they may cause a great deal of sweat buildup at the point of contact when they are used in hot environments (Berger, 2003). Similar to foam earplugs, earmuffs can provide a high amount of attenuation. They provide higher attenuation at mid/high frequencies than earplugs while the opposite is true for low frequencies (see Figure 11) (Casali & Berger, 1996).

**Helmets.** Helmets provide head and hearing protection at the same time by covering most of the head (see Figure 12). They are usually used by pilots and tank crews, and are rarely used in industry (Berger, 2003).
Figure 11. Attenuation provided by earplug, earmuff, or both worn together (Used with permission of Berger, 2003). Permission also granted by the American Industrial Hygiene Association.

Figure 12. Helmets’ design (Used with permission of Berger, 2003). Permission also granted by the American Industrial Hygiene Association.
Specialized Hearing Protection Devices

In certain surrounding conditions, listeners need to protect their hearing during noisy conditions while being able to communicate during quiet conditions. For example, combat-zone soldiers need to protect their hearing during firing, but during quiet periods they need to be able to communicate and hear any suspicious movements. The attenuation behavior of the conventional passive HPDs provides no advantage for these situations. They attenuate surrounding sounds, with a nonlinear increment in attenuation as the frequency of ambient noise increases, regardless of their levels, which is why they are sometimes called level-independent or amplitude-insensitive HPDs (Casali, 2005). To satisfy any special need for the users of HPDs, as explained by the previous scenario, different specialized (i.e., augmented) hearing protectors have been manufactured.

Augmented passive hearing protection devices. Augmented passive HPDs use passive (i.e., non-electronic) elements to overcome some of the aforementioned shortcomings associated with conventional passive HPDs. As explained before, conventional passive HPDs attenuate high frequencies more than low frequencies. As a result, they compromise listeners’ pitch perception (i.e., distort the acoustical information of the received auditory signal). Pitch perception becomes crucial at certain circumstances, for instance when workers need to detect high-frequency-rich alarms. Better pitch perception is provided by a type of hearing protectors called uniform (i.e., flat) attenuation hearing protectors (Figure 13). These HPDs exhibit constant attenuation (+/- 10 dB) in the 100 - 8000 Hz frequency range (Figure 14), which is achieved by the use of an orifice. The use of these HPDs at high levels of noise can be
hazardous to wearers’ hearing since they provide a moderate amount of attenuation. Thus, their use becomes preferable at low to mid levels of noise exposure (i.e., less than 90 dBA) (Berger, 2003).

Figure 13. Uniform (i.e., flat) attenuation hearing protectors (Used with permission of Casali & Berger, 1996). Permission also granted by Taylor & Francis Group.

Figure 14. Uniform/flat earplugs’ attenuation [custom molded ER-15 and premolded ER-20] versus conventional earplugs’ attenuation (Used with permission of Berger, 2003). Permission also granted by the American Industrial Hygiene Association.
Another type of augmented passive HPDs is the passive *amplitude-sensitive* or *level-dependent* HPDs. These HPDs satisfy the need to listen or communicate during quiet periods and to provide hearing protection during periods of noise. This is performed by placing a valve or sharp-edged orifice inside either an earplug or a duct in an earmuff cup. During quiet periods, the laminar flow of the surrounding sound waves is allowed to pass through the orifice while during the noise periods the orifice will avoid the passage of the turbulent flow of the surrounding sound waves (Berger, 2003). These devices provide little attenuation at background noise levels below 110 dBA, especially at frequencies less than 1000 Hz (Casali, 2005). Thus, they are not suited to be used in continuous noise exposure which has levels ranging from 85 dBA to 110 dBA. Instead, their use is preferred in intermittent and impulsive noise exposures where quiet periods have levels below 85 dBA. One of the popular amplitude-sensitive HPDs available in the market, circa mid-2010, is the E-A-R/3M Combat Arms™ earplug (CAE) (see Figure 15). These earplugs have two sides which have different functions. The green side is a conventional passive premolded earplug which provides constant attenuation. Clearly, this side provides soldiers with a constant amount of attenuation against continuous noise exposure (e.g., noise exists during tank transportation). The other side is an amplitude-sensitive earplug which allows soldiers in the battle field to be aware of any surrounding threatening movements or sounds during quiet periods while protect them from any sudden or intense sounds (e.g., gunfire) (Figure 16) (Casali, 2005).
Augmented active (electronic) hearing protection devices. Unlike the augmented passive HPDs which have no electronics, augmented active HPDs overcome the shortcomings associated with conventional passive HPDs with the
assistance of an electronic system. *Level-dependent sound transmission* HPDs are one of the common types of active hearing protectors. As shown in Figure 17, they consist of a microphone attached to the earmuff cup, an amplifier, and earphones enclosed inside the earcups. This electronic system amplifies specific frequency components of the signal picked by the microphones (e.g., critical frequency range for speech intelligibility) during quiet periods to a maximum level of 82 - 85 dBA under the earcup. Accordingly, these HPDs provide better signal detection and speech comprehension during quiet periods. To protect listeners from high noise exposures during noise periods, the electronic system shuts off and the hearing protector reverts to a passive mode (i.e., act as a conventional passive earmuff) as noise levels increased to hazardous levels (Casali, 2005).

*Figure 17. Main components of the active level-dependent HPDs (Used with permission of Casali, 2005). Permission also granted by the Internoise president, Dr. Samir Gerges.*
The microphones’ design for level-dependent active earmuffs has critical practical implications for the safety of their users. Two designs are available for these HPDs, the *diotic* and *dichotic* designs. In the diotic design, *only* one microphone, which is attached to one earcup, passes the same signal to both earphones. Consequently, it compromises listeners’ localization performance since it deforms the binaural information associated with the passed signal. On the other hand, the dichotic design provides better localization performance. This is achieved by having one microphone attached to each earcup separately (i.e., a total of two microphones) so the signal picked by the left/right microphone is passed to the left/right earphone and consequently keeps the signal’s binaural cues intact (Berger, 2003).

**Comfort of Hearing Protection Devices**

Comfort provided by hearing protectors is one of the important factors to insure achieving the designed amount of attenuation (Casali, Lam, & Epps, 1987; Park & Casali, 1991). This is justified by the common saying, “The best HPD is the one that workers will wear” (Park & Casali, 1991, p.152). Some studies indicated that workers’ first complaint about the side effects of HPDs is regarding discomfort (Casali et al., 1987). A direct result of workers’ feeling of discomfort is the adjustment of the hearing protector or even its removal. Consequently, the aimed attenuation is compromised or unattained. For example, if the HPD is not worn for only 15 minutes in an 8-hour work period (around 3% of the total work period), then its Noise Reduction Rating (NRR) will be reduced by 5 dB (around 20% decrement in the HPD protection) (Park & Casali, 1991).
To assess workers’ comfort experience with fitted HPDs, Casali et al. (1987) developed a subjective rating scale. The scale consists of different rating criteria. The rating for each item is used to develop a Comfort Index (CI) which is used to express the subjects’ general assessment of the HPD’s level of comfort.

Due to the common use of HPDs in the construction industry, in addition to their detrimental effect on localizing sounds (see the next chapter), their effect on listeners’ performance in localizing backup alarms was investigated in the research herein.
HUMAN SOUND LOCALIZATION

Being able to localize sound sources is critical for the safety of humans. They use their localization ability to avoid any approaching dangers (e.g., backing vehicles). Although humans rely primarily on their visual system to localize objects in their environment, they utilize their auditory system to localize sound-emitting objects when their vision is compromised (Blauert, 1997). To localize environmental objects, their direction (i.e., azimuth ($\theta$) and elevation ($\delta$)) and distance ($r$) should be identified (Figure 18) (Moore, 2004). To identify the direction of sound sources, three acoustical cues are utilized by the human auditory system: *Interaural Time Difference* (ITD), *Interaural Level Difference* (ILD), and the *Spectral Cues Provided by the Pinna* (Flamme, 2002; Gelfand, 2004; Hartmann, 1999; Moore, 2004; Wolfe et al., 2006).

*Figure 18.* The coordinate system ($\theta$, $\delta$, and $r$) used for sound localization.
**Interaural Time Difference**

Interaural Time Difference (ITD) is defined as the difference in sound arrival time between the two ears (Gelfand, 2004; Moore, 2004; Wolfe et al., 2006). Sounds that are emitted from left sources arrive to the left ear before the right ear and vice versa for sounds emitted from right sources. This lag in the arrival time provides a localization cue for listeners. But ITD is a frequency-dependent localization cue. Theoretically, at low frequencies, the sound wavelength is larger than the human head’s dimensions. This causes the sound wave to bend around the head and enables listeners to compare the time of arrival of the sound wave between the two ears, thereby using it to localize the source of the sound wave (Gelfand, 2004; Moore, 2004). Feddersen, Sandel, Teas, & Jeffress (1957) investigated the relationship between the azimuthal location of a tonal sound and the ITD. As shown in Figure 19, their results indicated that ITD has a minimum value of 0 microseconds (μs) when the sound source is located in front of or behind the head and a maximum value of 690 μs when the sound source opposes the ear. Although the range of ITD values across the azimuth are in microseconds, humans’ threshold for detecting ITD has been shown to vary from 10 μs to 75 μs according to the type of the auditory signal (Klumpp & Eady, 1956).

**Interaural Level Difference**

Interaural Level Difference (ILD) is defined as the difference in sound pressure level between the two ears (Gelfand, 2004; Moore, 2004; Wolfe et al., 2006). Sounds that are emitted from left sources will be perceived as being louder in the left ear than the right ear and vice versa for sounds emitted from right sources. Theoretically, at high frequencies, the sound wavelength is smaller than human head’s dimensions. This
produces a head shadow (see Figure 20) which enables listeners to detect ILD. As with ITD, ILD is a frequency-dependent localization cue. Feddersen et al. (1957) showed that ILD is an effective cue to localize high-frequency-tonal sounds in azimuth. As shown in Figure 21, ILD values at frequencies below 500 Hz are very small and provide negligible information to localize tonal sounds. However, ILD increases consistently as the frequency increases where it can reach a maximum value of 20 dB at 6000 Hz (Feddersen et al., 1957).

Figure 19. Interaural time difference (ITD) for sinusoidal sound as a function of azimuth (from Feddersen et al., 1957). Permission granted by the Acoustical Society of America.

Figure 20. The human head shadow as a result of high frequency sound waves.
Spectral Cues Provided by the Pinna

Even though ILD and ITD cues are crucial for azimuthal localization, they render no acoustical information in two conditions: 1) when the sound source is located in front of or behind the listener where they approximately equal zero (see Figures 19 and 21), and 2) when the source of sound travels inside the cone of confusion (see Figure 22) where they remain constant (Gelfand, 2004; Wolfe et al., 2006). In these conditions, the human auditory system utilizes the spectral cues provided by the pinna (also known as pinna cues or monaural spectral cues) for localization. During the transmission of the
sound wave from its source to the eardrum, the pinna, due to its convolutions, alters the spectral characteristics of the sound wave in a direction-specific way (see Figure 23). This is more salient for high (greater than 4000 Hz) than low frequencies (Gelfand, 2004; Shaw, 1974).

Musicant & Butler (1984) investigated the role of the spectral cues provided by the pinna on azimuthal sound localization. They tested their subjects under four signal conditions (broadband noise, 4 kHz hi-pass noise, 4 kHz low-pass noise, and 1 kHz low-pass noise) and two ear conditions (open and occluded ear). Their results showed that in the open ear condition, the broadband and the 4 kHz hi-pass noises provided better sound localization performance (less front/back confusion) than the 4 kHz low-pass noise, and 1 kHz low-pass noise. They concluded from these results that frequencies above 4 kHz are crucial for sound localization proficiency, especially front/rear judgments.

Figure 22. The cone of confusion.
Figure 23. Direction-specific spectrums at the eardrum (from Shaw, 1974). Permission granted by the Acoustical Society of America.
Sound Localization and Auditory Warning Signals

Although localizing sound sources is very important for the safety of listeners, the designers of auditory warning signals/alarms paid little attention to the design principle of signal localizability as opposed to other principles (e.g., signal detectability). This is justified by the localization deficiency associated with most of the auditory warning signals/alarms (Stanton & Edworthy, 1999). For instance, most of the emergency vehicles’ (e.g., ambulances, police cars, fire trucks, etc) sirens are designed with a frequency range of 500 - 1800 Hz. Clearly, this range is not optimal to localize emergency vehicles’ sirens (Withington, 1999). In literature, most of the research focused solely on humans’ ability to localize pure tones, white noises, or similar sounds. Little effort has been directed to test how listeners localize real world auditory warning signals. One of these efforts is the study conducted by Withington (1996) where she tested how listeners, with normal hearing, localized different types of real world sirens, which have a frequency range of 670 - 1100 Hz and 500 - 1800 Hz, in addition to newly-designed broadband sounds. The study’s results showed 82% correct front/back judgments when listeners tried to localize the broadband sounds. In contrast, their correct front/back judgments dropped to 44% when they tried to localize other narrowband sirens. The same trend also revealed by correct right/left judgments: 93% for the broadband sounds and 79% for the narrowband sirens.

Backup alarms offer no exception for being deficient in terms of localizability. In 1998, Laroche & Lefebvre indicated that most of the commercial backup alarms emit near-pure tone signals, with a dominant frequency in the 1000 - 1400 Hz frequency range and thus lacking the frequencies that foster sound localization. In addition, the
Society of Automotive Engineers (SAE) standard J994b-2009 mandates a predominant frequency in the frequency range of 700 - 2800 Hz for backup alarms, which has limited coverage of localizable frequencies.

In the literature, most of the research done on testing the effectiveness of backup alarms focused on the effect of HPDs, background noise levels, workers’ hearing status, and the acoustic features of the backup alarm signal on the signal detection (Casali et al., 2004; Casali & Wright, 1995; Laroche & Lefebvre, 1998; Lovejoy, 2008; Robinson & Casali, 1995). There is only one study found in the literature that tested the effect of the backup alarm’s acoustic features on workers azimuthal localization performance. Withington (2004) used subjective measures to assess workers’ performance in localizing conventional backup alarms as well as broadband backup alarms (white noise). The resultant data revealed better localization performance when listeners were asked to localize broadband backup alarms than when they were asked to localize the narrowband conventional backup alarms. Although these results sound promising in terms of improving on-foot workers’ safety, factors other than the acoustic features of backup alarms that may compromise workers’ localization ability (e.g., noise exposure and use of hearing protectors) were not considered in her study. In addition, white noise backup alarm is not familiar as an alarm.

**Sound Localization and Noise Exposure**

Background noise is inherent in most of the occupational environments (e.g., construction sites). Although most of the researchers studied sound localization in quiet conditions, few included the background noise levels in their experimental design (Flamme, 2002).
In 1996, Good & Gilkey tested normal-hearing listeners’ ability to localize a broadband signal at different signal-to-noise (S/N) ratios that ranged from +14 to -13. Their results showed that the decrement in S/N ratio was associated with decrement in localization performance. This decrement in localization performance was more salient in front/back judgments. The results provided by other researchers (Lorenzi, Gatehouse, & Lever, 1999) also confirmed the findings of Good & Gilkey (1996).

**Sound Localization and Hearing Protection Devices**

Hearing protectors are used as a defender to workers’ hearing. However, one of their drawbacks is revealed by their detrimental effect on sound localization (Berger, 2003; Berger & Casali, 1997; Nixon & Berger, 1998). Research on the effect of hearing protectors on sound localization received little attention compared to their effect on speech intelligibility and signal detection. This research effort will be overviewed chronologically and according to the type of the tested hearing protectors as follows.

**Sound localization and passive HPDs.** One of the earliest investigative studies on the effect of hearing protectors on humans’ localization performance was conducted by Atherley & Noble (1970). They tested the effect of earmuffs on listeners’ ability to localize sounds in the azimuth dimension after many complaints from foundry workers regarding the adverse effect of earmuffs on their directional hearing. The study’s 15 participants were asked to localize a 1 kHz pure tone in an anechoic room under two aural conditions: unoccluded or while wearing a conventional passive earmuff. Six loudspeakers were placed in the azimuth dimension, 60° apart from each other and 1.32 m away from the participant, to present the tested signal. The study’s results showed 76% of correct judgments when the listeners’ ears were unoccluded. After
being fitted with the passive earmuff, the percentage of their correct judgments dropped significantly to 50%. Also, the right/left localization errors under the earmuff condition (113 right/left errors) were significantly more than those under the unoccluded condition (13 right/left errors). Finally, even though there was no significant difference between earmuff and unoccluded conditions in terms of rearward (i.e., judging front sounds as coming from back) or frontward (i.e., judging back sounds as coming from front) errors, rearward errors under the earmuff condition were more than frontward errors. They concluded that their resultant data may provide evidence on the detrimental effect of hearing protectors on workers’ localization performance.

In 1971, Atherley & Else reconducted the previous experiment in a reverberant environment due to the fact that most industrial environment is reflective in nature. Their experimental setup was identical to the one provided by Atherley & Noble (1970) except that there were 10 participants instead of 15, the test environment was reverberant instead of anechoic, and the speakers were placed 1.5 m away from the participants. The resultant decremental trend in sound localization performance associated with using earmuffs in reverberant environment resembled the one provided by Atherley & Noble (1970). Again, correct localization judgments dropped significantly from 54.5% when listeners’ ears were unoccluded to 39.6% when they were fitted with the earmuff. In addition, listeners’ made 16 right/left localization errors in the unoccluded condition and significantly more right/left localization errors (i.e., 42 errors) in the earmuff condition. A valuable observation was the effect of the reverberant environment on the magnitudes of the percentage of correct responses. As shown, for the anechoic environment, the percentages were 76% at the unoccluded condition and 50% at the
earmuff condition while for the reverberant environment they dropped to 54.5% and 39.6% respectively.

In 1972, Noble & Russell tried to explain theoretically the findings of Atherley & Noble (1970) and Atherley & Else (1971). They postulated that earmuffs disruptive behavior on localization performance maybe attributed to their destroying effect on the signals’ binaural cues, their destroying effect on the pinna spectral cues, or their attenuation. To test these three hypotheses they conducted two separate experiments. The experimental setup was identical to the one provided by Atherley & Noble (1970) except that the listeners were asked to localize a broadband white noise in addition to the 1 kHz pure tone. Also, the listeners were tested at unoccluded, commercial earmuff, and modified (by removing the earmuff’s headband) earmuff conditions for the first experiment and at unoccluded, foam earplug, and commercial earmuff conditions for the second experiment. The results of their first experiment indicated statistically-significant better localization performance (i.e., more correct responses and fewer errors) when listeners localized the broadband white noise than when they localized the pure tone. In addition, they performed better in localization at unoccluded condition compared to the commercial and modified earmuffs conditions. The difference in localization performance was only statistically-significant between the unoccluded condition and the modified earmuff condition while it was not between the two earmuff conditions. From their first experiment findings, they believed that listeners’ localization performance was compromised by earmuffs due to their detrimental effect on the spectral cues provided by the pinna. This was supported by the better performance provided by the broadband white noise at unoccluded condition. In addition, when listeners localized the white
noise signal, the decrement in correct responses associated with the earmuffs was
greater than when they localized the pure tone. This was due to the fact that the pinna
spectral cues were more salient at broadband than narrowband signals. Also, the lack
of a statistically-significant difference between the commercial and modified earmuff did
not support the hypothesized effect of earmuffs on binaural cues. The third hypothesis,
the attenuation hypothesis, gained no ground by the results of their second experiment.
Their second experiment's results indicated that earplugs provided significantly more
localization errors than the unoccluded condition in only one type of the three reported
errors. This behavior by the earplugs was not interpretable by any of the three proposed
hypotheses. Again, the earmuff provided the worst localization performance since it
provided significantly less correct responses and more errors in two of the three
reported errors than the earplug and the unoccluded condition. Noble & Russell
concluded that earplugs are favored over earmuffs when localizing sounds correctly is
crucial for workers' safety.

In 1976, Russell & Noble tried to interpret their previous findings of the earplug's
behavior on sound localization. They described the pinna as a shadow producer for the
high-frequency components of broadband signals emanating from behind the listeners.
As a result, these signals will reach their ears rich in low frequencies. Since earplugs
provided the same behavior by attenuating high frequencies more than low frequencies,
they believed that listeners fitted with earplugs will perceive signals as coming from
behind regardless of their actual source. They hypothesized that earplugs transform
signals’ localization information while earmuffs reduce it. To test their hypothesis, they
investigated how certain were 45 participants in their localization decisions. Certain
decisions associated with incorrect judgments were considered as an evidence for information transformation. On the other hand, uncertain decisions were considered as evidence for information reduction. Listeners were asked to localize a broadband white noise emanating from one of five loudspeakers placed at 30°, 60°, 90°, 120°, and 150° to their left side at a semi-anechoic room. After providing their localization responses they were asked to rate their decisions’ certainty on a 6 rating scales. Three aural conditions were adopted in their study: unoccluded, earplug, and earmuff. Listeners’ localization performance was demonstrated in terms of three measures: correct responses, rearward responses, and frontward responses. Their results showed the following: 1) no significant difference existed between the unoccluded and earplug conditions in terms of correct responses, 2) significant difference in correct responses (less correct responses) existed between the earmuff and the other two conditions combined, 3) earplugs provided significantly more rearward errors than unoccluded condition, 4) earmuff provided significantly more rearward errors than unoccluded and earplug conditions combined, 5) The magnitude of the frontward errors was significantly greater under the earmuff condition than those under the unoccluded and earplugs conditions combined, but this was not the case between the unoccluded and earplug conditions, 6) there was no significant difference in correct responses’ certainty between all listening conditions, 7) there was no significant difference between the unoccluded and earplug listening conditions in rearward errors’ certainty while it existed between the earmuff (less certainty) and the other two conditions combined, and 8) no significant difference in frontward errors’ certainty existed between all listening conditions. Their findings supported their proposed hypothesis of information transformation for earplugs.
In most of the previous localization studies, participants’ head movement was restricted. There is some scientific evidence that head movements may improve horizontal sound localization (Moore, 2004). Accordingly, Noble (1981) investigated listeners localization performance while they were equipped with passive earmuffs versus their performance while they were unoccluded under head movement condition. Twenty one participants with normal hearing were asked to localize a narrowband noise centered at 1 kHz in a semi-anechoic room. Listeners were tested at the following aural conditions: restricted-head movement (RHM) while wearing earmuffs, free-head movement (FHM) while wearing earmuffs and FHM while unoccluded. The resultant data indicated more accurate horizontal localization decisions at FHM-earmuff condition (50%) than the RHM-earmuff condition (24%). When listeners were free to move their heads unoccluded, their horizontal localization decisions were accurate most of the time (95%). A novel measure for localization performance was proposed in this study, localization response time. The results showed an average of 6.25 seconds to deliver accurate responses at the FHM-earmuff condition and 1.84 seconds at the FHM-unoccluded. Clearly, this indicated more confident decisions in unoccluded condition compared to earmuff condition.

In 2001, Bolia, D’Angelo, Mishler, & Morris continued the research effort on the effect of passive hearing protectors on sound localization. Three listening conditions were considered in their study: unoccluded, E-A-R classic foam earplug, and E-A-R circum-aural earmuff (model-3000). They tested the proficiency of 6 listeners with normal hearing and restricted head movements in localizing broadband pink noises in an anechoic chamber. Their results confirmed the previous findings of less horizontal
localization proficiency at hearing protection conditions compared to unoccluded condition.

More evidence on the detrimental effect of hearing protectors on horizontal localization performance was reported by Brungart, Kordik, Simpson, & McKinley (2003). The horizontal localization performance for eight normal-hearing listeners was estimated in an anechoic chamber. They provided significantly less localization accuracy at single hearing protection conditions and double hearing protection conditions compared to the unoccluded listening condition. The new finding reported by their study demonstrated by significantly less localization performance when listeners were fitted with earplugs in addition to earmuffs (i.e., double hearing protection) than when they were fitted with only earplugs or earmuffs (i.e., single hearing protection).

**Sound localization and augmented HPDs.** As described before, augmented HPDs are designed to improve wearers’ auditory perception (e.g., pitch perception). Consequently, these HPDs attracted many researchers in human auditory spatial perception to investigate their effect on humans’ directional hearing. In 1982, Howse & Elfner observed the azimuthal localization behavior of six normal-hearing listeners in an anechoic environment. Listeners, with their heads immobile, were instructed to localize a broadband noise signal while they were unoccluded, fitted with an inactive (i.e., in a passive mode) dichotic hearing protection system, fitted with an active dichotic hearing protection system, fitted with an inactive diotic hearing protection system, and fitted with an active diotic hearing protection system. All hearing protection systems were enclosed inside a military headgear. The two passive hearing protection systems detrimentally affected sound localization performance, and the diotic active system severely
destroyed listeners’ perception of sounds’ loci. Although the signal’s ITD and ILD were
supposed to be intact in the dichotic active system, it provided a slightly better
localization performance than the diotic active system.

The results of Howse & Elfner (1982) from the military version of active HPDs
motivated Noble, Murray, & Waugh (1990) to investigate the effect of the industrial
version of these HPDs on humans’ localization performance. Ten listeners with normal
hearing were recruited for this purpose. They were seated in an anechoic room and
instructed to localize noise signals in the horizontal and vertical planes with free head
movements. Seven listening conditions were adopted: unoccluded, wearing passive
foam earplug, wearing passive earmuff, wearing two different types of dichotic active
earmuffs, and wearing two different types of diotic active earmuffs. Listeners were able
to localize accurately in the unoccluded condition in an approximately perfect way.
When they were fitted with the passive hearing protectors or the two dichotic active
earmuffs, they provided significantly less accurate responses than in the unoccluded
condition. No difference in localization performance was reported between these
hearing protectors. Conversely, the two diotic active earmuffs significantly destroyed
locale perception more than any other listening condition.

Most of the previous effort in studying the effect of hearing protectors on sound
localization was applied to a specific segment of the population, listeners with normal
hearing. Consequently, Abel & Hay (1996) explored how hearing-impaired listeners’
azimuthal localization performance was affected by hearing protectors. In their study,
they tested 48 individuals with normal hearing and 23 with hearing loss in a
semi-reverberant room in a fixated head condition. All listeners assessed the azimuthal
location of two types of signals, narrowband noises centered at 500 Hz and 4000 Hz, while they were unoccluded, fitted with passive earplug, fitted with passive earmuff, and fitted with dichotic active earmuff. In addition, the effect of two noise conditions, quiet and 65 dBA of background noise, and two groups of age were considered. Their results showed that at the quiet and 500 Hz condition, listeners’ localization performance was degraded significantly by using the hearing protectors; no difference in localization performance was observed between the HPDs in the quiet condition. The same results were observed for the 4000 Hz except that the active muff significantly degraded localization performance more than the passive HPDs. Exposing listeners to the 65 dBA noise deteriorated their performance in localizing the 500 Hz signal at the unoccluded condition, but it did not affect their performance under any HPD. Listeners were more resistant to the effect of noise on localizing the 4000 Hz signal. The effect of hearing impairment on localization performance was salient when listeners with dysfunctional hearing were unable to hear the 4000 Hz signal after they were fitted with the passive earplug or the passive earmuff.

Flat-attenuation HPDs are another form of augmented HPDs that provide a uniform attenuation across frequencies from 100 Hz to 8000 Hz. Their potential localization benefits have been investigated by Vause & Grantham (1999). They tested the azimuthal localization ability of six individuals with normal hearing in an anechoic environment. They were asked to localize an M16 rifle cocking presented from one of 20 loudspeakers scattered in a 180° arc placed in front of them or beside their left side. The effect of the military Kevlar helmet, E-A-R passive foam earplug, and ER25 uniform-attenuation earplug on azimuthal sound localization was assessed. For this
purpose, listeners were tested under eight experimental conditions: bare head/open ears, bare head/E-A-R passive foam earplug, bare head/ER25 musician’s uniform-attenuation earplug, Kevlar helmet/open ears, Kevlar helmet/E-A-R passive foam earplug, Kevlar helmet/ER25 musician’s uniform-attenuation earplug, and two more bare head/open ears conditions. Their results revealed no significant effect of the Kevlar helmet when it was worn alone on listeners’ localization performance. However, when listeners were equipped with the Kevlar helmet and one of the earplugs together, their localization accuracy degraded significantly. Also, the ER25 uniform-attenuation earplug offered no advantage in localization since it provided significantly more localization errors than the bare head/open ear condition.

The localization behavior of the Combat Arms™ earplug, another augmented hearing protector, was assessed in 2006 by Babeu, Binseel, Mermagen, & Letowski. They tested the localization performance for 12 normal-hearing individuals in a semi-anechoic room. They were asked to localize a 65 dBA uttered word that peaked at 200 to 1000 Hz. Listeners’ sound localization ability was tested under five aural conditions and two background noise conditions. The aural conditions were: unoccluded, premolded earplug, foam earplug, the yellow side (i.e., amplitude-sensitive side) of the Combat Arms™ earplug, and the green side (i.e., passive side) of the Combat Arms™ earplug. The background noise conditions were 30 dBA (i.e., quiet) and 58 dBA of pink noise. When listeners were fitted with the Combat Arms™ earplugs, they provided better localization performance than when they were fitted with the foam earplug. In addition, while listeners were equipped with the hearing protectors, they
provided less localization errors under the 58 dBA background noise condition than under the quiet condition.

**Distance Perception and Hearing Protection Devices**

Research applied on the topic of humans’ auditory distance perception received little attention from researchers compared to the research applied on humans’ auditory direction perception (i.e., horizontal and vertical sound localization) (Zahorik, Brungart, & Bronkhorst, 2005). For the workers’ safety, it is critical to judge accurately *from where* and *how far* is any approaching/backing vehicle. This is especially true when the approaching/backing vehicle is outside the workers’ field of view. In 1985, McMurtry & Mershon conducted one of the few studies that focused on the effect of hearing protectors on humans’ distance perception. They recruited 162 listeners with normal hearing to judge the distance of a noise signal presented from three distances, 0.75, 2.1, and 6 m. Listeners were tested under three conditions: quiet condition (60 dBA), noisy condition (90 dBA), and noisy condition while wearing passive foam earplugs. The results showed approximately correct distance judgments under the quiet condition. However, increasing the background noise level from 60 to 90 dBA significantly degraded listeners’ distance judgments (i.e., they perceived distances closer than where they were). When listeners were fitted with the foam earplug, their performance resembled the one provided at the noisy condition. McMurtry & Mershon believed that high levels of background noise mask the weak-reflected sound waves more than the direct sound waves from the source of the signal. As a result, listeners perceived the source of sound as being closer than its actual distance.
Literature Gap for HPD Effects on Azimuthal Sound Localization and Distance Perception

According to the aforementioned literature review, there is not enough attention applied on testing humans’ azimuthal localization performance at high levels of background noise (e.g., 90 dBA), which may exist in many industrial settings (e.g., construction sites), while wearing electronic or non-electronic HPDs. In addition, Babeu et al. (2006) compared the azimuthal sound localization performance when listeners were fitted with premolded earplugs against when they were fitted with passive foam earplugs while using a signal that has most of its energy in the 200 to 1000 Hz range. This comparison would be more useful if the signal had most of its energy in the 200 to 4000 Hz range. This is because the spectral cues at these frequencies will help in comparing the foam earplug and premolded earplug in terms of the effect of the premolded earplug’s “handle” on the sound localization performance, especially the front/back discrimination. That is, the presence of the handle/stem may adversely affect the localization cues provided by the pinna. In addition, response time in the sound localization process was only considered in one experiment where only one conventional passive earmuff was tested. It may be of great interest to determine the response time while localizing an approaching signal (such as a backup alarm signal) under different types of HPDs, as such data may help in selecting the proper HPD type that can help its wearer avoid backup alarm accidents.

Also, McMurtry & Mershon (1985) tested the effect of only one type of HPDs on humans’ distance perception. A need exists to test the effect of other types of HPD on how far humans can detect auditory signals instead of how accurate they can assess
the location of auditory signals. This is important from the perspective of HPD-equipped workers' safety since they need to detect backup alarm signals while backing vehicles are as far away as possible. In doing so, they will have ample time to attend to, recognize, and localize backup alarm signals. In addition, they will have enough time to evade backing vehicles.
RESEARCH OBJECTIVES AND HYPOTHESES

Overview

From the previous literature review, it can be seen that research on sound localization ability in the 360° azimuth range while wearing different types of HPDs in very noisy environments such as construction sites is lacking. In addition, most of the sound localization studies made use of off-the-shelf selections for their HPDs; in other words, there was no apparent rationale for the selection of HPDs that are applicable for specific application environments, such as the construction site. Furthermore, laboratory signals in most previous research efforts have consisted of pure tones, white noise, or similar sounds, so the need existed to investigate common, real signals, such as backup alarms. In addition, investigating the effect of different HPDs on the distance at which real signals, such as backup alarms, are detectable (detection distance) is lacking.

It is clearly evident from the literature review that the ability to localize warning signals, verbal warnings from co-workers, or backup alarm signals from reversing vehicles is critical for the safety of construction workers. Although construction workers are encouraged to wear HPDs to avoid hearing loss, improper selection of the HPD type/design may impair the workers’ ability to localize important signals, which can create hazardous situations. In other words, it is a great mistake to try to solve a problem by creating another one. Also, improper selection of the HPD type/design may affect the detection distance. This is very crucial for workers’ safety since detecting
backup alarm signals at far distances will help provide them with ample time to react to any backing vehicles.

**Objectives**

The goal of this research was to evaluate how well or how poorly various HPDs foster localization of backup alarms (the most common industrial/construction warning signal), in addition to evaluating how well or how poorly various HPDs affect the detection distance. Specifically, the main research objectives were summarized as follows:

1. To investigate the accuracy (number of correct localization responses and the number of different types of errors in localization responses) and the speed of the sound localization decisions in the azimuth dimension under different types of HPDs. The devices used were the most recent technology in augmented passive and active HPDs available in the market circa mid-2010, in addition to the conventional passive earplugs and earmuffs that are marketed for the construction industry. All HPDs were compared against the unoccluded (open) ear.

2. To study the effect of different types and levels of background noises that are representative of those existing in construction sites on the accuracy and the speed of sound localization decisions in the azimuth dimension.

3. To test the effect of adding different frequency components to the standard backup alarm signal on the accuracy and the speed of sound localization decisions in the azimuth dimension.
4. To investigate how humans detect backup alarm signals in the distance dimension under different types of HPDs. The devices used were the most recent technology in augmented passive and active HPDs available in the market circa mid-2010, in addition to the conventional passive earplugs and earmuffs that are marketed for the construction industry. All HPDs were compared against the unoccluded ear.

5. To test the effect of the standard backup alarm signal and a commercially-available broadband backup alarm signal on the distance at detection.

Hypotheses

Parallel to these specific study objectives, the following hypotheses were formulated:

H1. Earplugs will provide more accurate (more correct responses and fewer errors) and quicker sound localization decisions in the azimuth dimension than earmuffs.

H2. Among all HPDs that tested in this study, the diotic earmuff will provide the least accurate and the slowest sound localization decisions in the azimuth dimension.

H3. The modified backup alarm signal will provide more accurate and quicker sound localization decisions in the azimuth dimension than the standard backup alarm signal.

H4. The high background noise level will result in less accurate and slower sound localization decisions in the azimuth dimension than the low background noise level.
H₅. Azimuthal sound localization performance under the classic foam earplug will be improved over the premolded earplug due to the potential adverse effect of the premolded earplug’s handle on the spectral cues afforded by the pinna/concha.
METHODOLOGY: FIRST EXPERIMENT

(Localizing Backup Alarm Signal in Azimuth Dimension)

Experimental Design

The participants’ horizontal (i.e., azimuthal) localization accuracy and response time on determining the angular direction of approach of a backup alarm were investigated by an 8×2×2 completely within-subjects experiment (Figure 24). Based on the aforementioned literature review, three variables were believed to influence listeners’ ability to localize backup alarm signals in industry and construction and were used to represent the independent variables of this experiment. These independent variables were: 1) the hearing protection condition (8 levels), 2) the level of background noise (2 levels), and 3) the type of backup alarm signal (2 levels). A discussion of each of the independent variables is provided below.

Independent Variables

Hearing protection condition variable. The hearing protection condition consisted of: 1) unoccluded (i.e., no HPD) condition, 2) Moldex Model-6604 foam passive earplug (SparkPlug™ earplug), 3) E-A-R/3M Ultrafit™ premolded passive earplug, 4) E-A-R/3M HiFi™ earplug, also marketed as the Etymotic ER-20™ earplug, (a uniform or “flat” attenuation HPD), 5) E-A-R/3M Arc™ earplug (a passive level-dependent HPD), 6) Bilsom Leightning™ L3HV passive earmuff, 7) a custom-made diotic electronic sound transmission earmuff, and 8) Bilsom Impact™ dichotic electronic sound transmission earmuff.
Figure 24. Experimental design block diagram for the first (localization) experiment.
From the myriad of HPDs that are commercially-available, the selection of those HPDs for this experiment was primarily based upon the following: 1) the device was known by the researcher, and/or advertised by the manufacturer, to be used on road construction sites; and/or, 2) the device incorporated special features (e.g., uniform attenuation, level-dependent attenuation, electronic sound pass-through) that were believed to have potential for improving situation awareness for the construction worker who needs to hear auditory warnings.

The noise in construction sites is intermittent by nature and construction workers are exposed to quiet periods as well as noise periods. In environments characterized with intermittent noise, the need exists for workers to be able to communicate during quiet periods in addition to being protected from high levels of noise during noise periods. As a result, three hearing protectors that were believed to fulfill this need were used in this study: the E-A-R/3M Arc™ earplug, a custom-made diotic earmuff, and the Bilsom Impact™ dichotic earmuff (see Figures 25d, 25f, and 25g). The E-A-R/3M Arc™ earplug is a two-ended earplug and it is an industrial version of the military Combat Arms™ earplug. The red end of this earplug, with a Noise Reduction Rating (NRR) of 22, provides constant protection from continuous noise. But the most valuable feature of this earplug resides in the yellow end which was the only end that was investigated in this study since the red end is essentially identical to one of the hearing protectors included in this study, i.e., the Ultrafit™. The yellow end (NRR = 0) contains a filter which allows soft sounds to pass through while suppress impulsive sounds. This is obviously beneficial for construction workers since the yellow end of the E-A-R/3M Arc™ earplug may help avoid workers’ feeling of isolation during quiet periods while
Figure 25. HPDs included in the first (localization) experiment: a) Moldex Model-6604 foam passive earplug (SparkPlug™ earplug), b) E-A-R/3M Ultrafit™ premolded passive earplug, c) E-A-R/3M HiFi™ earplug (a uniform or “flat” attenuation HPD), d) E-A-R/3M Arc™ earplug (a passive level-dependent HPD), e) Bilsom Leightning™ L3HV passive earmuff, f) a custom-made diotic electronic sound transmission earmuff, and g) Bilsom Impact™ dichotic electronic sound transmission earmuff.
protecting them against impulsive sounds during noise periods. The custom-made diotic earmuff and the Bilsom Impact™ dichotic earmuff (NRR = 23 in the passive mode of operation) are active (electronic) earmuffs, which are also known as sound restoration or sound pass-through devices. These earmuffs have microphones attached to the ear cups to pick and transmit ambient sounds (e.g., coworkers’ conversations, warning signals, etc) to electronic pass-through circuits that reside inside the ear cups. As described by the manufacturer (Howard Leight, 2010), during quiet surrounding conditions these circuits amplify ambient sounds in their passband to 82 dBA to improve listeners’ situation awareness. At the same time, the Bilsom Impact™ earmuffs protect listeners from high background noise levels (above 82 dBA as described by the manufacturer) since their pass-through circuits shut-off and the earmuff reverts to a passive mode. Again, these earmuffs are obviously purported to fulfill the aforementioned need for construction workers.

Also, construction sites are characterized by elevated background noise levels and therefore there is an extant need to protect construction workers from these elevated noise levels. The Moldex foam earplug (NRR = 33), Figure 25a, the E-A-R/3M Ultrafit™ premolded earplug (NRR = 25), Figure 25b, and the Bilsom Leightning™ Hi-Visibility L3HV passive earmuff (NRR = 30), Figure 25e, were selected due to their high attenuation values. These hearing protectors were believed to be applicable to the construction industry since they were expected to fulfill the need to protect construction workers from high background noise levels that existed in construction sites. In addition to their high attenuation, the use of this type of hearing protectors is prevalent in industry and construction.
Although the foam earplugs are considered advantageous in protecting listeners from intense sounds when properly inserted, they may cause a serious hygienic problem. This type of earplug requires a roll down by worker’s fingers for proper fitting. Given that construction workers’ hands are often exposed to dust and dirt, rolling down the foam earplug with contaminated hands and inserting them may transmit bacteria into the earcanals. A valuable alternative that provides a hygienic benefit is the reusable flanged polymer earplugs. Three flanged polymer earplugs were selected in this study: the E-A-R/3M UltraFit™ premolded earplug, the E-A-R/3M HiFi™ earplug (NRR = 12), and the E-A-R/3M Arc™ earplug (see Figures 25b, 25c, and 25d). The flanged polymer earplug consists of a handle or stem and flanges. Unlike the foam earplug, the whole cylinder of which gets in contact with hands of the workers, only the handle of the flanged polymer earplug is necessarily touched by the workers’ hands and this point always stay out of contact with the ears even after the plug is inserted. Thus, the flanged polymer earplugs were considered to be highly applicable to construction industry due to their hygienic benefits, in addition to their labeled high attenuation.

In addition to the rationale explained above for the inclusion of certain HPDs in this study, some of these HPDs have interesting features that were hypothesized to affect listeners' localization performance. The custom-made diotic earmuff and the Bilsom Impact™ dichotic earmuff were identical except for the design of their microphones. In the Bilsom Impact™ dichotic earmuff, one microphone attached to each ear cup picks up the ambient signal and feeds it to the ear cup matched to that microphone, providing true stereo hearing. In addition to its amplification advantages, as explained above, the dichotic earmuff was expected to provide more natural localization
performance than either passive or diotic muff. In contrast to this localization advantage for the Bilsom dichotic earmuff, the custom-made diotic earmuff was believed to degrade listeners’ localization performance due to its microphone design. This diotic earmuff was not a commercially-available product at the time of this writing, although such designs have been on the market for many years. This particular diotic earmuff was fabricated by the research team by customizing the Bilsom Impact™ dichotic earmuff. The microphones’ design of this customized diotic earmuff allowed the ambient signal to be picked up by only one of the microphones; the one attached to the left ear cup, and then the signal was transmitted to both ear cups simultaneously. The diotic earmuff was hypothesized to degrade listeners’ localization performance since its microphones’ design did not allow for transmission of the binaural cues needed for ITD and ILD benefits.

In addition to their hygienic benefits, as explained above, the E-A-R/3M HiFi™ earplug, and the E-A-R/3M Arc™ earplug were chosen since their attenuation profiles were expected to improve listeners’ localization performance. Unlike conventional passive earplugs which exhibit higher attenuation at high frequencies compared to attenuation at low frequencies, the E-A-R/3M HiFi™ (which has identical flange design to the E-A-R/3M Ultrafit™ premolded earplug) exhibits an approximately uniform attenuation in the 100 - 8000 Hz frequency range (see Appendix A). As described by the manufacturer, this uniform attenuation across the aforementioned frequency range improves the listener’s pitch perception. Thus, it was hypothesized that the E-A-R/3M HiFi™ earplug may improve listeners’ directional hearing. Regarding the E-A-R/3M Arc™ earplug, as described before, its yellow end (i.e., level-dependent end) provides
very low attenuation in the 125 - 1000 Hz frequency range (see Appendix A). This attenuation profile of the level-dependent end of the E-A-R/3M Arc™ earplug was thought to enable listeners to take better advantage of ITD localization cues and consequently improve their horizontal localization performance.

**Background noise level variable.** Two levels were investigated in this study: 60 dBA and 90 dBA (i.e., “low” and “high”, respectively). The lower level, 60 dBA, was selected since at this level the circuits of the custom-made diotic earmuff and the Bilsom dichotic earmuff were expected to amplify the surrounding sounds in this study (i.e., the backup alarm signal and the background noise). In addition, it is representative of the noise levels existing during quiet periods in many construction sites (Casali & Lancaster, 2008). The higher level, 90 dBA, was selected since it is representative of the noise levels existing during noise periods in many construction sites (Casali & Lancaster, 2008), and because it represents the noise Permissible Exposure Limit (PEL) (i.e., criterion level) of OSHA. In addition, at this level the circuits of the Bilsom Impact™ earmuff were advertised to shut-off, causing the earmuff to revert to a passive mode. The spectral intensity of these two levels was adjusted to represent the spectral distribution of a pink noise (i.e., flat-by-octave within +/- 3 dB). Among the different types of noises, according to their spectral intensity, the pink noise was selected since it is a powerful masker for narrowband frequencies. This is due to direct frequency masking as well as the upward spread of masking.

**Backup alarm signal variable.** The third independent variable was the type of the backup alarm signal. Two types were selected to investigate the listeners’ localization performance: a standard backup alarm and a spectrally-modified backup
alarm. As shown in Figure 26, the spectrum of the standard backup alarm peaks at three dominant frequencies of 1000, 1250, and 3150 Hz. As explained in the literature review, the frequencies that are considered advantageous for horizontal localization are those below 1500 Hz and above 3000 Hz. It is obvious that the standard backup alarm signal consisted of frequencies that are considered marginal to this important localization frequency range for ITD and ILD cues. Consequently, the spectrally-modified backup alarm signal was augmented by adding two primary frequency components of 400 Hz and 4000 Hz (see Figure 26). Obviously, the spectrally-modified backup alarm signal includes in its spectrum frequencies that are considered advantageous to horizontal sound localization. This is because the listeners have strong ITD cues produced by the 400 Hz frequency component and strong ILD cues provided by the 4000 Hz frequency component to use to localize the source of backup alarm signal when it emanates from the horizontal plane outside the vertical median plane. Additionally, the broad bandwidth of the spectrally-modified backup alarm signal was expected to help listeners in front-rear localization. This is because the broad bandwidth signals are considered to be rich in spectral cues which are critical for front-rear localization (Gelfand, 2004). The on-off pulse rate of the alarms was 60 pulses per minute.

**Participants**

A total of 12 participants (Age range: from 18 to 38 years; Gender: 8 males and 4 females) were recruited by the research team to serve as subjects in the first (localization) experiment. All of them were qualified based on three qualifying criteria: 1) normal hearing in both ears (i.e., defined as less than or equal to 25 dBHL at 250, 500,
1000, 1500, 2000, 3000, 4000, and 6000 Hz in both ears), 2) bilateral symmetry difference of less than or equal to 15 dBHL between the two ears (this was included to avoid any possible binaural hearing-related bias in localizing the backup alarms), and 3) passing successfully a familiarization session (as explained later).

Figure 26. Standard and spectrally-modified backup alarm spectra as used in the first (localization) experiment.

Apparatus

The participants' normal hearing and ear health was verified by using a Beltone Model 114 pure-tone audiometer and a Heine otoscope (Model-mini2000), respectively. These qualifying tests were performed in one of the rooms in the Virginia Tech Auditory
Systems Laboratory. Another room, with dimensions 19 ft long by 18 ft wide by 8.5 ft high, was selected to conduct the familiarization and experimental sessions. This room provided a hemi-anechoic sound field since it has a hard floor and ceiling and its walls were covered with an acoustic absorption foam sheets, manufactured by SONEX™. The reverberation time for this room, obtained in response to a standard backup alarm of 95 dBA that was suddenly shut-off, is shown in Figure 27. Reverberation time was measured as RT60 which is defined for a given frequency as: “the number of seconds it takes for the average sound pressure level in a room (originally in a steady state) to decrease 60 dB after the source is stopped” (Harris, 1998, p 4.8).

The noise generating system consisted of the following apparatus: 1) one Atlas Soundolier noise generator (Model-GPN-1200A), 2) two Sony amplifiers (Model-STR DE-135), 3) two AudioControl one-third octave equalizers (Model-C-131), 4) two Phoenix Gold speaker selectors (Model-VSS2), and 5) four Infinity loudspeakers (Model-SM-155) (Figure 28). The background noises were generated with the Atlas Soundolier noise generator and the 60 and 90 dBA levels were adjusted by the two Sony amplifiers. To present these levels selectively and on demand by the experimenter to the participants through the four Infinity loudspeakers, the two Phoenix Gold speaker selectors were used. Finally, the two one-third octave equalizers were used to provide the pink noise spectral intensity (i.e., flat-by-octave spectrum). The spectrum and broadband dBA levels of the background noise were verified before each experimental session, at the participant’s head position, by using a Larson-Davis 2800 Series Real-Time Spectrum Analyzer and a Larson-Davis model-2559 1/2-inch microphone, which was calibrated to 94 dBA at 1 kHz using a Quest QC-20 calibrator.
Figure 27. Reverberation time (RT60) for the test room, first (localization) experiment. Measurements were in octave bands centered at 1000, 1250, 3150 Hz, and in dBA.

Figure 28. Equipment used in the first (localization) experiment to generate background pink noise.
The two backup alarm signals were presented to the participants from a DELL laptop computer, where they were stored, through one of eight, Klipsch Comm Sat loudspeakers. These loudspeakers were placed in a circle at 6 feet away from the participant’s head center position and at a height of 46.2 inches (i.e., mean of male/female ear height) (Figures 29 and 30). Prior to the Klipsch loudspeakers, a Parasound Line Drive preamplifier (Model-P/LD-1100) and a Sony amplifier (STR-DE-135) were used to amplify the sound pressure level of the backup alarm signal to the correct levels shown in Appendix B. After this amplification, two Phoenix Gold VSS4 speaker selectors were used to direct the backup alarm signal selectively and on demand by the experimenter to one of the eight backup alarm loudspeakers (Figure 31).

Figure 29. Experimental test environment with loudspeaker placement for pink noise and for backup alarms in 360° azimuth. (An acoustically transparent curtain which was between the subject and the backup alarm loudspeakers is not shown) (Used with permission of Alali & Casali, 2011). Permission also granted by the Noise and Health Journal.
Figure 30. Photo of the experimental test environment with loudspeaker placement for pink noise and for backup alarms in 360° azimuth. (An acoustically transparent curtain which was between the subject and the backup alarm loudspeakers is not shown).

Figure 31. Equipment used in the first (localization) experiment to amplify the backup alarm signal and distribute it to the backup alarm loudspeakers.
All loudspeakers were obscured from the participant’s view by a black, acoustically-transparent curtain. The dBA levels of both backup alarm signals emanating from each of the eight loudspeakers were verified before each experimental session to match those in the table of Appendix B, at the participant’s head position, by using the Larson-Davis 2800 Spectrum Analyzer and the calibrated microphone described previously.

While the above-described apparatus was used to provide the testing conditions, the participants’ responses were collected by a Fujitsu tablet PC, Microframe 2-digit timer (Model-6320), and a pushbutton. Installed on the tablet PC was a customized LabVIEW program. This program was used to present a 360° digital compass and an ENTER DIRECTION digital button to the participant (see Figure 32). A stylus attached to the tablet PC was used by the subject to move the needle on the 360° digital compass towards the perceived direction of the approaching backup alarm signal and to press the ENTER DIRECTION digital button to store the digital compass input. The participant’s interaction with the LabVIEW program was monitored by a 17” DELL monitor connected to the video-out port of the tablet PC. The timer and the pushbutton were used to collect the localization response times in seconds (see Figure 33).

Finally, a wholly separate apparatus was configured to test the manufacturer’s claims that the Impact™ dichotic earmuff reverts to a passive mode when the surrounding noise levels exceeds 82 dBA. This claim was tested by using a custom-made acoustical test fixture (per ISO/DIS6290) with a 1-inch microphone connected to a Larson-Davis 3200D spectrum analyzer. An objective test was performed to determine the actual under-earcup output of two samples of the
Figure 32. LabVIEW program interface.

Figure 33. Subject’s station with Microframe 2-digit timer, pushbutton, Fujitsu Tablet PC, and the acoustically transparent curtain. This view is from the subject’s perspective during the localization experimental trials.
Bilsom Impact™ dichotic muff in noise levels widely spanning 82 dBA. In a noise field of surrounding, incident pink noise, presented at constant individual levels ranging from 75 dBA to 90 dBA, the Impact™ dichotic earmuff yielded under-earcup levels of approximately 90–91 dBA with the gain set to maximum (as it was set in the experiment described herein). Thus, these results demonstrated that the Impact™ earmuff’s transmission circuit did not verify the manufacturer’s claims; however, it did appear that at the 75 dBA incident level, since the under-earcup level was 90-91 dBA, the broadband gain was approximately 15 dBA.

**Backup alarm signal synthesis and simulation**

To produce the spectrally-modified backup alarm signal, the two additional frequencies, 400 Hz and 4000 Hz, were added to the standard backup alarm signal by using Adobe Audition™ Software. In addition, the same software was used to control the backup alarm signals as if they were approaching the participants’ position by increasing the signals’ sound pressure level over time. Both standard and modified backup alarm signals were simulated as signals approaching the subject at a fixed speed. This approach was considered, instead of presenting a signal with a fixed intensity, since it represents the real world scenario. The signal simulated a vehicle approaching from 240 feet away to a position 19 feet away from the listener. The rate of increase in the sound pressure level of the backup alarm signal was calibrated to simulate an approach speed of 10 mph; this speed was selected because it represented one of the faster reversing speeds among construction vehicles (J. G. Casali, personal communication, 2007). The change in sound pressure level of the backup alarm at the
participant’s ear, corresponding to the simulated distance from the participant, is depicted in Figure 34. A detailed calculation of these levels is provided in Appendix B.

![Backup alarm’s simulated approach toward participant, with dBA increment by distance (Used with permission of Alali & Casali, 2011). Permission also granted by the Noise and Health Journal.]

**Figure 34.** Backup alarm’s simulated approach toward participant, with dBA increment by distance (Used with permission of Alali & Casali, 2011). Permission also granted by the Noise and Health Journal.

**Procedure**

*Screening and familiarization session.* Before starting this session, a consent from each participant to participate was provided by his/her signature on the informed consent form, after reading of this form and receiving answers to any questions (see Appendix C). The screening part of this session started by asking each participant specific questions to verify his/her healthy ear condition, in addition to inspecting the condition of his/her eardrums and earcanals by using the otoscope. Next participants’ hearing was checked using the audiometer. Before starting the familiarization part of this session, each hearing protector was fitted on each participant by the experimenter.
to insure proper fitting. To start the familiarization session, each participant was instructed in the procedures of the localization task and practiced by localizing 16 beeps (8 beeps presented from each Klipsch loudspeaker twice each) of the spectrally-modified backup alarm signal in a quiet background condition (60 dBA) while unoccluded. To pass the familiarization session successfully and becoming qualified to proceed to the experimental sessions, the participant must have correctly localized at least 8 out of the 16 beeps; otherwise he/she was dismissed.

**Experimental sessions.** Each participant underwent four experimental sessions which were scheduled on four different days to avoid any fatigue effect on the study results. Each session included one-fourth of the full set of factorial combinations of the independent variables (see Figure 24), consisting of two (out of eight) hearing protection conditions, both background noise levels, and both backup alarm conditions which were each presented twice. A different hearing protection condition was assigned to the participant in each experimental session. The order of this assignment was performed by counterbalancing according to a repeated-non-identical complete Latin Square. Presentation of both backup alarm signals was accomplished in a random fashion within a session, as were the background noise levels, to avoid order effects. In each experimental session, participants performed the localization task in 128 experimental trials, consisting of two sets of 64 trials for each of the two HPDs tested in this session. The 64 experimental trials consisted of presentation of two redundant (i.e., identical) trials for each of the two different backup alarm signals, from each of the eight Klipsch speakers for each of the two background noise conditions. The two identical trials were not presented consecutively, but were presented randomly across the 64 total session
trials. Upon arrival, the participant was seated in a chair placed in the middle of the test room, and instructed on the experimental procedures. Before starting the experimental session, the experimenter fitted the assigned HPD properly on the participant’s ears. Next, the participant performed the 64 experimental trials of the localization task. In each experimental trial, the participant, wearing the assigned HPD (or open ear condition) was presented with one of the background noise levels and one of the backup alarm types. He/she had 15 seconds, from the moment when the backup alarm signal first sounded, to press the pushbutton, to stop the timer, and then point on the tablet PC’s 360° compass towards his/her estimate of the alarm’s angular direction. The participant was allowed to move his/her head, but not his/her torso, for better estimation of the alarm’s angular direction. If the participant did not respond within 15 seconds, he/she was then instructed to make his/her immediate best guess for the perceived angular direction of the backup alarm signal, using the compass on the digital tablet. After each experimental session, the participant was instructed to provide his/her impressions on comfort rating scale, shown in Appendix D, for the fit-tested HPD.

**Dependent Measures**

*Localization Accuracy.* Four objective, quantitative dependent measures were collected to measure the effects of the independent variables on participants’ localization accuracy: 1) *percentage correct localization*, 2) *percentage of right-left localization errors*, 3) *percentage of front-rear localization errors*, and 4) *localization absolute deviation in degrees* (see Figure 35).

Any participant’s response less than or equal to 22.5° to the right or left of the actual source of the backup alarm signal was considered correct (Figure 35a), for the
measure of percentage correct localization. The participants’ responses were
categorized in the right-left localization errors if the backup alarm signal emanated from
one of the loudspeakers numbered with 2, 3, or 4, Figure 35b, and the participant’s
response on the Tablet PC digital compass was in the angular range of 180° - 360°. The
same thing applied if the backup alarm signal emanated from one of the loudspeakers
numbered with 6, 7, or 8, Figure 35b, and the participant’s response on the Tablet PC
digital compass was in the angular range of 0° - 180°. By using the same approach
adopted in the right-left localization errors, the front-rear localization errors were
identified by considering the backup alarm signal emanating from one of the
loudspeakers numbered with 8, 1, or 2, Figure 35c, as emanating from any angle
ranging from 90° to 270°. The same thing applied if the backup alarm signal emanated
from one of the loudspeakers numbered with 4, 5, or 6, Figure 35c, and the participant’s
response on the Tablet PC digital compass was in the angular ranges of 270° - 360° or
0° - 90°. The localization absolute deviation in degrees from the alarm’s azimuthal
location was determined by getting the absolute value of degrees of error in judgment
from the alarm’s actual direction, which ranged from 0° to 180° (see Figure 35d).

**Localization Speed.** An objective, quantitative dependent measure was
collected to measure the effects of the independent variables on participants’
localization speed which was the localization response time in seconds, which ranged
from 0 to 15 seconds.
Figure 35. Illustration for the localization accuracy dependent measures for the first (localization) experiment. a) correct localization, b) right-left localization errors, c) front-rear localization errors, and d) localization absolute deviation in degrees.
DATA REDUCTION AND ANALYSIS: FIRST EXPERIMENT
(Localizing Backup Alarm Signal in Azimuth Dimension)

Data Reduction

The stored participants’ responses from the Tablet PC 360° digital compass were exported to a Microsoft Excel™ program to produce the four localization accuracy dependent measures. On the other hand, the participants’ localization response times, which were gathered manually from the timer on paper sheets, were manually inserted into the Microsoft Excel™ program worksheets. For each participant, the data was collected while he/she was exposed to one of the hearing protection conditions, one of the background noise levels, and one of the backup alarm signals. These data provided two sets of 8 responses (beeps presented from each of the eight Klipsch loudspeakers twice each). To produce the percentage correct localization, the number of correct responses under each of the two sets of 8 responses was divided by 8 and multiplied by 100. The percentage of right-left localization errors and the percentage of front-rear localization errors were produced in the same way as the percentage correct localization except the number of these errors were divided by six, instead of eight, and multiplied by 100. This number represents the total number of loudspeakers except loudspeakers numbered with 1 and 5 for the calculations of percentage of right-left localization errors, and numbered with 3 and 7 for the calculations of percentage of front-rear localization errors (see Figures 35b and 35c). By averaging (i.e., using the arithmetic mean) the numbers in the two sets of 8 responses for each of the five measure (i.e., four accuracy measures and one response time), one data point for each
participant was produced to represent his/her response on each dependent measure (i.e., in each block of Figure 24).

The data collected from the comfort rating scales (Appendix D) was inserted manually into the Microsoft Excel™ program worksheets. Participants’ responses were converted to numerical values ranging from 1 to 7. This range represents the seven steps of each of the comfort rating scale with 1 representing the extreme left and 7 representing the extreme right. These data was used to provide one Comfort Index (CI) for each participant at each HPD. This was performed by finding any statistically-significant correlation between any comfort rating scale and the most general Uncomfortable/Comfortable scale. Any scale which showed a significant correlation with the Uncomfortable/Comfortable scale was included, in addition to the Uncomfortable/Comfortable scale, to develop the CIs. This was done by summing the numerical values of these scales. Before this summation was performed, the numerical values in each scale which showed a negative significant correlation with the most general Uncomfortable/Comfortable scale was reversed (i.e., 7 to 1, 6 to 2, etc), in order to properly equate the scales’ directionality.

Data Analysis

The main as well as the interaction effects of the independent variables on each of the five dependent measures were examined by a separate within-subject Analysis of Variance (ANOVA). Any statistically-significant main or interaction effects revealed by ANOVA were based on a significance level (α) of 0.05. To show any statistically-significant difference in sound localization performance between the levels of each of these main and interaction effects, Tukey’s Honestly Significant Difference
(HSD) test was applied. Again, these statistically-significant differences were based on a chosen significance level (α) of 0.05.

The Statistical Analysis Software (SAS) program was used to compute the ANOVAs, and the Statistical Minitab software, in addition to the Microsoft Excel™ program, were used to generate the mean and 95% confidence intervals’ graphs. On all graphs plotted herein, means with different letters (as used in coding) are significantly different at \( p \leq 0.05 \) in either the ANOVA or post hoc test, whichever was the final analysis step for that variable or interaction.

To find the aforementioned significant correlation between any of the comfort rating scales and the most general Uncomfortable/Comfortable scale, a Spearman correlation test was adopted. The Spearman correlation was selected instead of other parametric types of correlation, since the collected data was treated as ordinal data. Two criteria were selected to show any statistically-significant association correlation: a significance level (α) of 0.05, and an absolute value of the Spearman correlation coefficient (\( r_s \)) greater than 0.45. To find any significant difference between the comfort levels of the HPDs the non-parametric Friedman test was used, at an α-level of 0.05. Again, this Friedman test was selected due to the ordinal nature of the collected comfort rating data. Any significant difference revealed by the Friedman test was further analyzed by the Wilcoxon Signed Rank Test at an α-level of 0.05.

The Spearman correlation test, the non-parametric Friedman test, and the Wilcoxon Signed Rank Test were performed on computer by using the Statistical Package for the Social Sciences (SPSS).
RESULTS: FIRST EXPERIMENT

(Localizing Backup Alarm Signal in Azimuth Dimension)

Hearing Protection Device (HPD) Main Effects

The main effect of the HPDs was statistically-significant on all five dependent measures as revealed by the ANOVAs. The results shown in Tables 4, 5, 6, 7, and 8 indicated a significant main effect for HPDs on percentage correct localization, $F(7,77) = 59.2$, $p < 0.0001$, on percentage of right-left localization errors, $F(7,77) = 42.7$, $p < 0.0001$, on percentage of front-rear localization errors, $F(7,77) = 43.0$, $p < 0.0001$, on absolute deviation in degrees from the backup alarm’s actual direction, $F(7,77) = 92.6$, $p < 0.0001$, and on localization response time, $F(7,77) = 17.2$, $p < 0.0001$.

Table 4.

ANOVA Summary table for the percentage correct localization (bold text indicates significance at $p \leq 0.05$).

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<th>Source*</th>
<th>df</th>
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<th>MS</th>
<th>$F^{**}$</th>
<th>$Pr&gt;F$</th>
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<td>HPD×BNL×BU</td>
<td>7</td>
<td>447.5</td>
<td>63.9</td>
<td>63.9</td>
<td>0.7</td>
</tr>
<tr>
<td>HPD×BNL×BU×S</td>
<td>77</td>
<td>6373.6</td>
<td>82.7</td>
<td>82.7</td>
<td></td>
</tr>
</tbody>
</table>

*HPD = Hearing Protection Device, BNL = Background Noise Level, BU = Backup Alarm, S = Subjects.
**Each $F$-ratio consists of the source of variance under test in the same row, divided by the error term for that source in the immediately following row.
Table 5.
ANOVA Summary table for the percentage of right-left localization errors (bold text indicates significance at p ≤ 0.05).

<table>
<thead>
<tr>
<th>Source*</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F**</th>
<th>Pr&gt;F</th>
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<tbody>
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<td>HPD</td>
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<td>41838.6</td>
<td>5976.9</td>
<td>42.7</td>
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</tr>
<tr>
<td>HPD×S</td>
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<td>------</td>
</tr>
<tr>
<td>BNL</td>
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<td>5924.6</td>
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<td>BNL×S</td>
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<td>284.2</td>
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</tr>
<tr>
<td>BU</td>
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<td>1497.5</td>
<td>15.4</td>
<td>0.0024</td>
</tr>
<tr>
<td>BU×S</td>
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<td>1069.6</td>
<td>97.2</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>HPD×BNL</td>
<td>7</td>
<td>1105.1</td>
<td>157.8</td>
<td>1.8</td>
<td>0.0946</td>
</tr>
<tr>
<td>HPD×BNL×S</td>
<td>77</td>
<td>6666.1</td>
<td>86.5</td>
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<td>------</td>
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<td>HPD×BU</td>
<td>7</td>
<td>1301.9</td>
<td>185.9</td>
<td>2.7</td>
<td>0.0128</td>
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<td>HPD×BU×S</td>
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<td>5175.9</td>
<td>67.2</td>
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<tr>
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<td>764.0</td>
<td>18.0</td>
<td>0.0014</td>
</tr>
<tr>
<td>BNL×BU×S</td>
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<td>466.3</td>
<td>42.3</td>
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</tr>
<tr>
<td>HPD×BNL×BU</td>
<td>7</td>
<td>658.0</td>
<td>94.0</td>
<td>1.8</td>
<td>0.1001</td>
</tr>
<tr>
<td>HPD×BNL×BU×S</td>
<td>77</td>
<td>4031.5</td>
<td>52.3</td>
<td>------</td>
<td>------</td>
</tr>
</tbody>
</table>

*HPD = Hearing Protection Device, BNL = Background Noise Level, BU = Backup Alarm, S = Subjects.
**Each F-ratio consists of the source of variance under test in the same row, divided by the error term for that source in the immediately following row.

Table 6.
ANOVA Summary table for the percentage of front-rear localization errors (bold text indicates significance at p ≤ 0.05).

<table>
<thead>
<tr>
<th>Source*</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F**</th>
<th>Pr&gt;F</th>
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<td>HPD</td>
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<td>57560.7</td>
<td>8222.9</td>
<td>43.0</td>
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<td>HPD×S</td>
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<tr>
<td>BNL</td>
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<td>9733.7</td>
<td>28.3</td>
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<td>3781.8</td>
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<td>------</td>
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<tr>
<td>BU</td>
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<td>234.3</td>
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<td>BU×S</td>
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<td>598.9</td>
<td>54.4</td>
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<td>------</td>
</tr>
<tr>
<td>HPD×BNL</td>
<td>7</td>
<td>3049.7</td>
<td>435.6</td>
<td>4.8</td>
<td>0.0001</td>
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<td>HPD×BNL×S</td>
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<td>6941.5</td>
<td>90.1</td>
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<tr>
<td>HPD×BU</td>
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<td>90.5</td>
<td>1.7</td>
<td>0.1033</td>
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<tr>
<td>HPD×BU×S</td>
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<td>3914.9</td>
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<tr>
<td>BNL×BU</td>
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<td>350.1</td>
<td>350.1</td>
<td>5.7</td>
<td>0.0349</td>
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<tr>
<td>BNL×BU×S</td>
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<td>665.5</td>
<td>60.5</td>
<td>------</td>
<td>------</td>
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<tr>
<td>HPD×BNL×BU</td>
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<td>506.3</td>
<td>72.3</td>
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<td>0.3966</td>
</tr>
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<td>HPD×BNL×BU×S</td>
<td>77</td>
<td>5248.8</td>
<td>68.1</td>
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</tr>
</tbody>
</table>

*HPD = Hearing Protection Device, BNL = Background Noise Level, BU = Backup Alarm, S = Subjects.
**Each F-ratio consists of the source of variance under test in the same row, divided by the error term for that source in the immediately following row.
Table 7.
ANOVA Summary table for the absolute deviation in degrees from the backup alarm source (bold text indicates significance at p ≤ 0.05).

<table>
<thead>
<tr>
<th>Source*</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
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<th>Pr&gt;F</th>
</tr>
</thead>
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<td>26778.8</td>
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<td>BNL</td>
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<td>31079.2</td>
<td>31079.2</td>
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<td>4257.1</td>
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<td>BU</td>
<td>1</td>
<td>2207.7</td>
<td>2207.7</td>
<td>25.9</td>
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<tr>
<td>BU×S</td>
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<td>936.8</td>
<td>85.1</td>
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<tr>
<td>HPD×BNL</td>
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<td>6769.6</td>
<td>967.0</td>
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<td>&lt;0.0001</td>
</tr>
<tr>
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<td>1236.9</td>
<td>176.7</td>
<td>3.3</td>
<td>0.0039</td>
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<td>4106.1</td>
<td>53.3</td>
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<tr>
<td>BNL×BU</td>
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<td>1146.8</td>
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<tr>
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<td>669.1</td>
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<td>5691.6</td>
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</tbody>
</table>

*HPD = Hearing Protection Device, BNL = Background Noise Level, BU = Backup Alarm, S = Subjects.

**Each F-ratio consists of the source of variance under test in the same row, divided by the error term for that source in the immediately following row.

Table 8.
ANOVA Summary table for the localization response time (bold text indicates significance at p ≤ 0.05).

<table>
<thead>
<tr>
<th>Source*</th>
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<th>MS</th>
<th>F**</th>
<th>Pr&gt;F</th>
</tr>
</thead>
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<td>653.6</td>
<td>93.4</td>
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<td>&lt;0.0001</td>
</tr>
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<td>418.1</td>
<td>5.4</td>
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<td>3251.7</td>
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<td>28.3</td>
<td>79.6</td>
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</tr>
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<td>BU×S</td>
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<td>3.9</td>
<td>0.4</td>
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</tr>
<tr>
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<td>98.9</td>
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<td>&lt;0.0001</td>
</tr>
<tr>
<td>HPD×BNL×S</td>
<td>77</td>
<td>171.9</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HPD×BU</td>
<td>7</td>
<td>3.0</td>
<td>0.4</td>
<td>1.6</td>
<td>0.2</td>
</tr>
<tr>
<td>HPD×BU×S</td>
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<td>20.8</td>
<td>0.3</td>
<td></td>
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</tr>
<tr>
<td>BNL×BU</td>
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<td>0.7</td>
<td>0.7</td>
<td>1.6</td>
<td>0.2</td>
</tr>
<tr>
<td>BNL×BU×S</td>
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<td>5.1</td>
<td>0.5</td>
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</tr>
<tr>
<td>HPD×BNL×BU</td>
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<td>2.7</td>
<td>0.4</td>
<td>1.9</td>
<td>0.1</td>
</tr>
<tr>
<td>HPD×BNL×BU×S</td>
<td>77</td>
<td>15.5</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*HPD = Hearing Protection Device, BNL = Background Noise Level, BU = Backup Alarm, S = Subjects.

**Each F-ratio consists of the source of variance under test in the same row, divided by the error term for that source in the immediately following row.

The Tukey's test indicated that on all dependent measures except the localization response time, the only statistically-significant difference between the listening conditions existed between the diotic earmuff and all other listening conditions. The same test indicated that there were no significant differences in localization response time between any of the HPDs or the open ear, except for the diotic earmuff
condition, which provided significantly longer localization response times than the open

The E-A-R/3M HiFi™ earplug provided the highest magnitude in percentage
correct localization (83.9%) and the lowest magnitudes in the percentage of right-left
localization errors (2.4%), in the percentage of front-rear localization errors (4.0%), and
in the absolute deviation in degrees from the backup alarm’s actual direction (11.8°)
(see Figures 36, 37, 38, and 39). In contrast, the custom diotic earmuff provided the
lowest percentage correct localization (15.8%), the highest percentage of right-left
localization errors (36.5%), the highest percentage of front-rear localization errors
(43.8%), and the highest absolute deviation in degrees from the backup alarm’s actual
direction (83.2°) (see Figures 36, 37, 38, and 39). In terms of the speed of localization
decisions, the open ear condition and the E-A-R/3M Arc™ earplug provided the lowest
magnitude of localization response time (5.8 seconds each) while the diotic earmuff
provided the highest (10.0 seconds) (see Figure 40).

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Figure 36. Main effect of HPDs on percentage correct localization, with mean values shown on bars with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey’s test.
Figure 37. Main effect of HPDs on the percentage of right-left localization errors, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey’s test.
Figure 38. Main effect of HPDs on the percentage of front-rear localization errors, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey’s test.
Figure 39. Main effect of HPDs on localization absolute deviation in degrees, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey's test.
Figure 40. Main effect of HPDs on localization response time, with mean values shown on bars with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey’s test.
Background Noise Level (BNL) Main Effects

The main effect of the background noise level was statistically-significant on all five dependent measures as shown by the ANOVAs. These statistics were

\[ F(1,11) = 103.7, \ p < 0.0001, \] for the percentage correct responses (see Table 4),

\[ F(1,11) = 20.8, \ p = 0.0008, \] for percentage of right-left localization errors (see Table 5),

\[ F(1,11) = 28.3, \ p = 0.0002, \] for percentage of front-rear localization errors (see Table 6),

\[ F(1,11) = 80.3, \ p < 0.0001, \] for localization absolute deviation in degrees (see Table 7),

and \[ F(1,11) = 116.3, \ p < 0.0001, \] for localization response time in seconds (see Table 8). For four of the five dependent measures, localization performance was half as good (or less) in 90 dBA noise as compared to 60 dBA, in this main effect of noise level. At 60 dBA, the mean values were 81.4\% for correct localization, 5.4\% for right-left localization errors, 7.2\% for front-rear localization errors, 17.5^\circ for localization absolute deviation, and 4.3 seconds for localization response time (Figures 41, 42, 43, 44, and 45). As the noise level increased to 90 dBA, the means significantly were decreased/increased to 54.7\% for correct responses, 13.3\% for right-left localization errors, 17.3\% for front-rear localization errors, 35.5^\circ for localization absolute deviation, and 10.2 seconds for localization response time (Figures 41, 42, 43, 44, and 45). From these background noise level main effect results, it is evident that the 90 dBA pink noise level, a level that is common to some industries and certainly to road construction in particular (Casali & Lancaster, 2008) results in much poorer localization of a backup alarm than does a relatively quiet 60 dBA pink noise level.
Figure 41. Main effect of background noise level on percentage correct localization, with mean values shown on bars with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$).
Figure 42. Main effect of background noise level on the percentage of right-left localization errors, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$).
Figure 43. Main effect of background noise level on the percentage of front-rear localization errors, with 95% confidence intervals plotted. Means with the same letter are not significantly different (p ≤ 0.05).
Figure 44. Main effect of background noise level on localization absolute deviation in degrees, with 95% confidence intervals plotted. Means with the same letter are not significantly different (p ≤ 0.05).
Figure 45. Main effect of background noise level on localization response time, with mean values shown on bars with 95% confidence intervals plotted. Means with the same letter are not significantly different (p ≤ 0.05).
Backup Alarm Signal (BU) Main Effects

The backup alarm main effect compared the two alarms, standard and spectrally-modified, the spectra for which appears in Figure 26. The main effect of the type of the backup alarm signal on four of five dependent measures, the sole exception being percentage of front-rear localization errors, was statistically-significant as shown by the ANOVAs. These statistics were $F(1,11) = 11.3, p = 0.0063$, for the percentage correct localization (see Table 4), $F(1,11) = 15.4, p = 0.0024$, for percentage of right-left localization errors (see Table 5), $F(1,11) = 25.9, p = 0.0003$, for localization absolute deviation in degrees, (see Table 7), and $F(1,11) = 79.6, p < 0.0001$, for localization response time in seconds (see Table 8). Although the improvements provided by the spectrally-modified alarm on these dependent measures were consistent and statistically-significant, they were numerically small. However, small numerical improvements in accuracy and response time could have great safety implications, as will be explained later. Listeners provided the following mean values when they localized the standard backup alarm: 66.1% for correct localization, 11.3% for right-left localization errors, 28.9° for localization absolute deviation, and 7.5 seconds for localization response time (Figures 46, 47, 48, and 49). When they localized the spectrally-modified backup alarm, the means changed to 70.0% for correct responses (a 3.9% improvement), 7.4% for right-left localization errors (a 3.9% improvement), 24.1° for localization absolute deviation (a 4.8° improvement), and 7.0 seconds for localization response time (a 0.5 seconds improvement).
Figure 46. Main effect of backup alarm type on percentage correct localization, with mean values shown on bars with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$).
Figure 47. Main effect of backup alarm type on the percentage of right-left localization errors, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$).
Figure 48. Main effect of backup alarm type on localization absolute deviation in degrees, with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$).
Figure 49. Main effect of backup alarm type on localization response time, with mean values shown on bars with 95% confidence intervals plotted. Means with the same letter are not significantly different (p ≤ 0.05).
HPD and Background Noise Level Interaction Effects

The ANOVA revealed a statistically-significant interaction between HPD and background noise level on percentage correct localization, $F(7,77) = 9.5, p < 0.0001$, Table 4, on percentage of front-rear localization errors, $F(7,77) = 4.8, p = 0.0001$, Table 6, on localization absolute deviation in degrees, $F(7,77) = 7.2, p < 0.0001$, Table 7, and on localization response time, $F(7,77) = 6.3, p < 0.0001$, Table 8. The primary interest in this two-way interaction was whether or not there was an advantage with certain HPDs at a given noise level. Therefore, to break down this interaction, a Tukey’s test was applied to test for HPD differences at each of the two noise levels.

In the 60 dBA background noise level, the Tukey’s test indicated that the Moldex foam earplug resulted in significantly lower percentage correct localization than any of the three E-A-R/3M earplugs (Ultrafit™, HiFi™, and Arc™) and the open ear condition, by approximately 20% or more (Figure 50). In addition, the diotic earmuff showed significantly lower percentage correct localization than any other listening condition. On the measure of percentage of front-rear localization errors, at 60 dBA there were no significant differences between any of the HPDs and the open ear condition, with the exception of the diotic earmuff which showed a significantly higher percentage of front-rear localization errors than any other listening condition (Figure 51). On the measure of localization absolute deviation in degrees, in 60 dBA pink noise, the Moldex foam earplug was associated with higher localization deviations than either the open ear condition or any of the three E-A-R/3M flanged earplugs, as was the Bilsom passive earmuff, while the diotic earmuff again showed the highest localization deviations of all HPDs (Figure 52). Also, at 60 dBA the Moldex foam earplug and the Bilsom passive
earmuff were associated with significantly higher response times than the open ear condition and the E-A-R/3M Arc™ earplug, while the diotic earmuff had the highest response time of all HPDs (Figure 53).

The best and worst localization performances at the background noise level of 60 dBA were shown by the range of the means for percentage correct localization (14.8% for the diotic earmuff to 98.9% for the unoccluded ear, Figure 50), for percentage of front-rear localization errors (0% for the open ear condition and the E-A-R/3M Arc™ earplug to 43.8% for the diotic earmuff, Figure 51), for localization absolute deviation in degrees (3.4° for the open ear condition to 83.8° for the diotic earmuff condition, Figure 52), and for the localization response time (2.6 seconds for the open ear condition to 8.2 seconds for the diotic earmuff condition, Figure 53).

In the 90 dBA background noise level, the Tukey’s test indicated that the Moldex foam earplug resulted in significantly lower percentage correct localization than only the E-A-R/3M HiFi™ earplug and that the Bilsom dichotic earmuff provided significantly less percentage correct localization than the E-A-R/3M Ultrafit™ and HiFi™ earplugs (Figure 50). On the measure of percentage of front-rear localization errors, the Bilsom dichotic earmuff again significantly degraded localization performance compared to the E-A-R/3M Ultrafit™ and HiFi™ earplugs (Figure 51). This significant degradation for the Bilsom dichotic earmuff on localization performance continued on the measure of localization absolute deviation in degrees since it showed more deviation than the three E-A-R/3M flanged earplugs (Figure 52). On all of the previous dependent measures (i.e., percentage correct localization, percentage of front-rear localization errors, localization absolute deviation in degrees, and localization response time), in 90 dBA
pink noise, there was no significant difference between any of the hearing protectors and the open ear condition (i.e., no HPD showed any advantage over the unoccluded condition) except for the diotic earmuff which significantly degraded, with much larger magnitudes, localization performance than any other listening condition. On the measure of localization response time only the open ear condition, the E-A-R/3M HiFi™ earplug, and the E-A-R/3M Arc™ earplug had significantly less localization response time than the custom diotic earmuff (Figure 53).

The best and worst localization performance at the background noise level of 90 dBA on each dependent measure were shown by the range of the means for percentage correct localization (16.7% for the diotic earmuff to 71.1% for the E-A-R/3M HiFi™ earplug, Figure 50), for percentage of front-rear localization errors (7.6% for E-A-R/3M HiFi™ earplug to 43.8% for the diotic earmuff, Figure 51), for localization absolute deviation in degrees (19.3° for the E-A-R/3M HiFi™ earplug to 82.6° for the diotic earmuff, Figure 52), and for localization response time (8.9 seconds for E-A-R/3M Arc™ earplug to 11.7 seconds for the diotic earmuff, Figure 53).
Figure 50. Interaction effect of HPDs and background noise level on percentage correct localization, with mean values shown on bars with 95% confidence intervals plotted. For each noise level, HPD means with the same letter (within each noise level) are not significantly different ($p \leq 0.05$) according to Tukey’s test.
Figure 51. Interaction effect of HPDs and background noise level on percentage of front-rear localization errors, with mean values shown on bars with 95% confidence intervals plotted. For each noise level, HPD means with the same letter (within each noise level) are not significantly different ($p \leq 0.05$) according to Tukey’s test.
Figure 52. Interaction effect of HPDs and background noise level on absolute deviation in degrees, with mean values shown on bars with 95% confidence intervals plotted. For each noise level, HPD means with the same letter (within each noise level) are not significantly different ($p \leq 0.05$) according to Tukey’s test.
Figure 53. Interaction effect of HPDs and background noise level on localization response time, with mean values shown on bars with 95% confidence intervals plotted. For each noise level, HPD means with the same letter (within each noise level) are not significantly different ($p \leq 0.05$) according to Tukey’s test.
HPD and Backup Alarm Signal Interaction Effects

The ANOVAs revealed a statistically-significant interaction between HPDs and backup alarm types on percentage correct localization, $F(7, 77) = 2.2, p = 0.0432$, Table 4, on percentage of right-left localization errors, $F(7, 77) = 2.7, p = 0.0128$, Table 5, and on localization absolute deviation in degrees, $F(7, 77) = 3.3, p = 0.0039$, Table 7. The primary interest in this two-way interaction was whether or not there was advantage with the spectrally-modified backup alarm at each HPD condition. Therefore, to break down this interaction, a Tukey’s test was applied to test for a backup alarm difference at each listening condition. Note that this analysis of the interaction was different than that previously discussed for the HPD and noise level interaction, which targeted difference between listening conditions at each noise level.

The spectrally-modified backup alarm signal was associated with an increment in percentage correct localization for most listening conditions except the diotic earmuff which showed a slight but statistically-nonsignificant decrement. The increments ranged from 0.5% for the E-A-R/3M HiFi™ earplug to 10.2% for the Bilsom dichotic earmuff. Two of these increments with the modified alarm were statistically-significant as indicated by Tukey’s test, the 10.2% increment for the Bilsom dichotic earmuff and the 8.8% increment for the Moldex SparkPlug™ earplug (see Figure 54).

The percentage of right-left localization errors demonstrated the same trend of improvement in localization performance when participants localized the spectrally-modified backup alarm as compared to the standard backup alarm. Most of the listening conditions were associated with a decrease in percentage of right-left localization errors except the HiFi™ earplug which showed a slight but
statistically-nonsignificant increase in errors. The range of the reduction in right-left errors was 0.3% for the E-A-R/3M Arc™ earplug to 9.7% for the Moldex foam earplug. Three of these reductions were statistically-significant as indicated by Tukey’s test, the 6.6% reduction in errors for the Bilsom dichotic earmuff, the 7.7% reduction for the diotic earmuff, and the 9.7% reduction for the Moldex foam earplug (see Figure 55).

For the localization absolute deviation in degrees, all of the listening conditions showed a consistent improvement, which ranged from 0.7° for the E-A-R/3M HiFi™ earplug to 10.7° for the Bilsom dichotic earmuff, with the spectrally-modified backup alarm signal (Figure 56). Again, two of these improvements with the spectrally-modified alarm were statistically-significant as indicated by Tukey’s test, the 10.7° improvement with the Bilsom dichotic earmuff and the 10.4° improvement for the Moldex foam earplug.
Figure 54. Interaction effect of HPDs and backup alarm signal on percentage correct localization, with mean values shown on bars with 95% confidence intervals plotted. For each HPD, backup alarm means with the same letter (within each HPD condition) are not significantly different ($p \leq 0.05$) according to Tukey’s test.
**Figure 55.** Interaction effect of HPDs and backup alarm signal on percentage of right-left localization errors, with mean values shown on bars with 95% confidence intervals plotted. For each HPD, backup alarm means with the same letter (within each HPD condition) are not significantly different ($p \leq 0.05$) according to Tukey’s test.
Figure 56. Interaction effect of HPDs and backup alarm signal on localization absolute deviation in degrees, with mean values shown on bars with 95% confidence intervals plotted. For each HPD, backup alarm means with the same letter (within each HPD condition) are not significantly different ($p \leq 0.05$) according to Tukey’s test.
Background Noise Level and Backup Alarm Signal Interaction Effects

The ANOVAs also revealed a statistically-significant interaction between background noise level and backup alarm signal type on three dependent measures: on percentage of right-left localization errors, \( F(1, 11) = 18.0, p = 0.0014 \), Table 5, on percentage of front-rear localization errors, \( F(1, 11) = 5.7, p = 0.0349 \), Table 6, and on localization absolute deviation in degrees, \( F(1, 11) = 11.2, p = 0.0065 \), Table 7. The interest in this two-way interaction was whether or not there was an advantage with the spectrally-modified backup alarm at a given noise level or as the noise level increased from 60 to 90 dBA. Therefore, to break down this interaction, a Tukey’s test was performed on all pairs of means within this interaction.

According to Tukey’s test, for all three measures (i.e., percentage of right-left localization errors, percentage of front-rear localization errors, and localization absolute deviation in degrees) there was no statistically-significant difference in localization performance between the two types of backup alarm signal at each noise level (Figures 57, 58, and 59). Also, there was a consistent trend of decreased localization performance as the background noise increased from 60 to 90 dBA which confirmed the previous results for the main effect of background noise level. For the standard backup alarm, this decrement due to increased noise level was demonstrated by 10.7% more right-left localization errors, 11.6% more front-rear localization errors, and 21.5° more localization absolute deviation (Figures 57, 58, and 59). When the participants localized the spectrally-modified backup alarm signal, they were more resistant to right-left and front-rear localization errors and had only 14.5° more localization absolute deviation as the noise level increased from 60 to 90 dBA (Figures 57, 58, and 59).
Figure 57. Interaction of backup alarm type and background noise level on percentage of right-left localization errors. Means with the same letter are not significantly different (p ≤ 0.05) according to Tukey’s test.
Figure 58. Interaction of backup alarm type and background noise level on percentage of front-rear localization errors. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey’s test.
Figure 59. Interaction of backup alarm type and background noise level on localization absolute deviation in degrees. Means with the same letter are not significantly different (p ≤ 0.05) according to Tukey’s test.
Hearing Protection Device (HPD) Comfort Rating

As described earlier, each subject completed a rating scale immediately after completing the localization trials with a given HPD. These rating scale data were subjected to a Spearman correlation test, which revealed a significant correlation (with $|r_s| > 0.45$ and $p < 0.05$) between six scales (Painless/Painful, No Uncomfortable Pressure/Uncomfortable Pressure, Intolerable/Tolerable, Not Bothersome/Bothersome, Soft/Hard, and Smooth/Rough) and the most general Uncomfortable/Comfortable scale (see Table 9). The scores on these scales, in addition to the Uncomfortable/Comfortable scale, were summed to develop the CI values. Before this summation was performed, the numerical values in each scale which showed a negative significant correlation with the most general Uncomfortable/Comfortable scale was reversed (i.e., 7 to 1, 6 to 2, etc), in order to properly equate the scales’ directionality. Figure 60 summarizes the median for the CI for each HPD. The minimum possible value for the CI was 7 and the maximum possible value was 49 (the higher the CI value, the greater the perceived comfort). A Friedman rank sum test was conducted to reveal any statistically-significant differences between the hearing protectors in terms of the composite CI. This test, with statistics of $X^2(6) = 8.179$, $p = 0.225$, indicated no significant differences between the tested HPDs in terms of the composite CI values.
Table 9. Spearman correlation coefficient ($r_s$) for each comfort rating scale with the Uncomfortable/Comfortable scale (bold text indicates statistical-significance at $p \leq 0.05$ where the scale’s $r_s$ is also $\geq 0.45$).

<table>
<thead>
<tr>
<th>Comfort Scale</th>
<th>$r_s$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Painless/Painful</td>
<td>-0.773</td>
<td>0.000</td>
</tr>
<tr>
<td>No Uncomfortable Pressure/Uncomfortable Pressure</td>
<td>-0.600</td>
<td>0.000</td>
</tr>
<tr>
<td>Intolerable/Tolerable</td>
<td>0.664</td>
<td>0.000</td>
</tr>
<tr>
<td>Tight/Loose</td>
<td>0.223</td>
<td>0.041</td>
</tr>
<tr>
<td>Not Bothersome/Bothersome</td>
<td>-0.820</td>
<td>0.000</td>
</tr>
<tr>
<td>Heavy/Light</td>
<td>0.233</td>
<td>0.033</td>
</tr>
<tr>
<td>Cumbersome/Not Cumbersome</td>
<td>0.289</td>
<td>0.008</td>
</tr>
<tr>
<td>Soft/Hard</td>
<td>-0.458</td>
<td>0.000</td>
</tr>
<tr>
<td>Cold/Hot</td>
<td>-0.031</td>
<td>0.777</td>
</tr>
<tr>
<td>Smooth/Rough</td>
<td>-0.686</td>
<td>0.000</td>
</tr>
<tr>
<td>Feeling of Complete Isolation/No Feeling of Isolation</td>
<td>0.215</td>
<td>0.049</td>
</tr>
<tr>
<td>Ear Open/Ear Blocked</td>
<td>-0.222</td>
<td>0.043</td>
</tr>
<tr>
<td>Ear Empty/Ear Full</td>
<td>-0.241</td>
<td>0.027</td>
</tr>
<tr>
<td>Confident Sound Localization Decisions/Nonconfident Sound Localization Decisions</td>
<td>-0.166</td>
<td>0.132</td>
</tr>
</tbody>
</table>

Figure 60. Comfort Index medians for the hearing protection devices (higher values indicate higher comfort). Comfort Index possible range: 7 to 49. Median values with the same letter are not significantly different at $p \leq 0.05$ according to a Friedman's Rank Sum test.
Hearing Protection Device (HPD) and Sound Localization Confidence scale

A separate analysis was conducted on the sound localization confidence scale to determine how confident listeners were in their localization decisions while using the various HPDs. A Friedman rank sum test was conducted to reveal any statistically-significant differences between the hearing protectors in terms of their perceived confidence in sound localization decisions. This test, with statistics of $X^2(6) = 30.078$, $p < 0.0001$, indicated significant differences between the tested HPDs in terms of the overall confidence in sound localization decisions. To pinpoint the source of this difference, a Wilcoxon Signed Rank Test was applied. As shown in Figure 61, the diotic earmuff provided the least confidence sound localization decisions as compared to any other HPD. This subjective result was in line with the objective results of listeners’ localization accuracy since the same earmuff provided the worst localization accuracy of any HPD in most of the main and interaction effects. In addition, listeners were more confident in localizing the backup alarm signal when they wore the uniform attenuation E-A-R/3M HiFi™ earplug than when they wore any of the high-attenuation HPDs (i.e., the Moldex foam earplug, the E-A-R/3M Ultrafit™ earplug, and the Bilsom passive earmuff). This increased user confidence with the uniform attenuation device provides evidence that it may be appropriate as an HPD for situations in which auditory vehicular alarms must be localized, as long as the noise exposures are not too severe for its moderate attenuation capabilities.
Figure 61. Medians for confidence in sound localization decisions for the hearing protection devices (higher values indicate less confidence in sound localization decisions). Possible range: 1 to 7. Median values with the same letter are not significantly different at $p \leq 0.05$ according to a Wilcoxon Signed Rank Test.
DISCUSSIONS AND CONCLUSIONS: FIRST EXPERIMENT
(Localizing Backup Alarm Signal in Azimuth Dimension)

Conclusions Regarding Passive HPDs and Localization Accuracy

The results yielded by this study slightly replicated the findings of the previous research, which generally showed a detrimental effect of passive hearing protectors on horizontal localization accuracy (see the literature review chapter). However, in this study, the graphs of the main effects of HPDs on participants’ localization accuracy (i.e., percentage correct localization, percentage of right-left localization errors, percentage of front-rear localization errors, and localization absolute deviation in degrees) indicated no statistically-significant detrimental effect of the passive HPDs (i.e., all HPDs except the Bilsom dichotic earmuff and the customized diotic earmuff) as compared with the open ear condition (see Figures 36, 37, 38 and 39). This trend of a non-detrimental effect of passive HPDs on localization accuracy was changed, as a function of the noise level, as revealed by the HPD and background noise interaction effects (See Figures 50, 51, and 52). At 60 dBA, the Moldex foam earplug provided significantly less percentage correct localization and more localization absolute deviation in degrees than the open ear condition and the three E-A-R/3M (i.e., Ultrafit™, HiFi™, and Arc™) earplugs. In addition, the Bilsom passive earmuff showed the same trend on localization absolute deviation in degrees. On three measures, percentage correct localization, percentage of front-rear localization errors, and localization absolute deviation in degrees, again at 60 dBA, the trend of no significant difference between the open ear condition and the three E-A-R/3M (i.e., Ultrafit™, HiFi™, and Arc™) earplugs was identical to the one shown in
the HPD main effect graphs. As the noise level increased to 90 dBA, all passive HPDs showed no advantage or disadvantage compared to the open ear condition on all of the aforementioned measures, in addition to showing no differences among themselves. The only advantage was at 90 dBA where the HiFi™ earplug provided significantly more percentage correct localization than the Moldex foam earplug.

On aggregate, the results revealed no significant difference in localization accuracy between the passive HPDs that had moderate attenuation (i.e., the E-A-R/3M HiFi™ and Arc™ earplugs) and the open ear condition. The passive HPDs having high attenuation values (i.e., Moldex foam earplug and Bilsom passive earmuff) showed the same behavior, except at the 60 dBA noise level, where they were worse in accuracy, as described above. These results are, in part, at odds with the results of most of the previous horizontal localization studies which showed the disruptive localization behavior of passive hearing protectors (see the literature review chapter). This is possibly due to the fact that listeners were allowed to move their heads in this experiment to aid in localization performance, as would be the case in actual job situations. As compared to a fixed head condition, previous research indicated that free head movements can improve localization performance in the horizontal plane while normal-hearing listeners wear earmuffs (Noble, 1981). However, head movement did not restore the localization performance in the unoccluded condition.

While these results are clearly situation- and HPD-specific, the lack of a passive HPD-induced disadvantage to localization in the 90 dBA noise condition (as compared to an open ear condition) does not give credence to the oft-given excuse by workers to
remove their hearing protectors when in the vicinity of backup alarm signals, at least for normal hearing individuals as were the participants in this study.

**Conclusions Regarding Active HPDs and Localization Accuracy**

The custom-made diotic earmuff significantly degraded listeners’ localization accuracy. This was indicated by its statistically-significant disruptive effect on localization in the main effects and interaction with background noise effects. As it was postulated, the single microphone design in the diotic earmuff clearly precludes the benefit of binaural auditory localization cues (i.e., ITD and ILD) since a single microphone feeds the same acoustic signal to both ears. These results corroborated those provided by Noble et al. (1990). Although Noble et al. also allowed head movements to provide better localization performance, their results indicated that the tested diotic earmuffs significantly disrupted localization accuracy as opposed to accuracies when a dichotic earmuff, passive earmuff, foam earplug, or unoccluded condition were tested.

Unlike the disruptive behavior of the customized diotic earmuff on localization performance, the dichotic earmuff showed no significant degradation on any of the localization accuracy dependent measures in the main effect. Similarly, at 60 dBA, the dichotic earmuff showed no significant difference compared to any other listening condition, except the condition of listening with the diotic earmuff, where the dichotic muff produced better performance. As the noise level increased to 90 dBA, the dichotic earmuff showed poorer percentage correct localization and more front-rear localization errors than the E-A-R/3M Ultrafit™ and HiFi™ earplugs. In addition, the localization absolute deviation in degrees achieved when using the dichotic earmuff was
significantly higher than those produced by the three E-A-R/3M earplugs. Also, at 90
dBA, the dichotic earmuff showed no advantage in horizontal localization accuracy over
the open ear condition. Overall, in the typical 90 dBA noise level found in road
construction, the dichotic earmuff was not the best HPD choice when compared to the
three flanged earplugs, and the diotic muff was much worse, and is clearly
contraindicated for construction work.

Dichotic earmuffs have been marketed as a superior alternative to their passive
earmuff counterparts. Although this may be true in terms of better communication and
signal detection in some instances, the lack of any significant improvement in
localization performance when using the Bilsom dichotic earmuff as compared to its
passive muff counterpart in the main and interaction effects, dispels this superiority.
Thus, the added cost and maintenance (e.g., battery) requirements of a dichotic muff of
this type cannot be justified, at least for workers with normal hearing. Of course, it must
be recognized that this study only investigated one model of dichotic sound
transmission earmuff, and thus the results are not generalizable to all other dichotic
devices on the market, which may differ in design features and electronic performance.

**Conclusions Regarding Passive HPDs and Localization Response Time**

When relying on backup alarms for forewarning, it is important to localize backing
vehicles quickly as well as accurately to evade them. Based on the results of the main
effects of HPDs, the open ear listening condition offers no advantage in localization
speed over the passive HPDs. This was also true in the interaction effect of HPDs and
the noise level of 90 dBA. At 60 dBA, there also was no difference between the three
E-A-R/3M flanged earplugs and the unoccluded condition. However, at 60 dBA the
Moldex foam earplug and the Bilsom passive earmuff significantly degraded localization speed compared to the unoccluded condition and the E-A-R/3M Arc™ earplug. Again, in the 90 dBA noise level the lack of advantage of the open ear condition compared to the passive hearing protectors in terms of localization response time does not provide any rationale for workers to remove their hearing protectors.

**Conclusions Regarding Active HPDs and Localization Response Time**

The previous degrading behavior of the customized diotic earmuff on localization accuracy was also replicated on localization response time. Although listeners consumed only 39% of their available time (i.e., 5.8 seconds) to localize the backup alarm signal while they were unoccluded, their response time significantly increased to 67% of time allowable when they were fitted with the customized diotic earmuff (see Figure 40). Also, this earmuff provided significantly slower localization responses than two of the tested passive earplugs, the E-A-R/3M HiFi™ and Arc™ earplugs. This behavior continued in the interaction effect between HPDs and 90 dBA on localization response time (see Figure 53). At 60 dBA, the diotic earmuff provided significantly slower localization speed than any other listening condition (see Figure 53). In the main and interaction effects on localization response time, the diotic earmuff provided the worst performance (i.e., 10 seconds in the main effect of HPDs, 8.2 seconds in the interaction effect between HPDs and 60 dBA, and 11.7 seconds in the interaction effect between HPDs and 90 dBA). The Bilsom dichotic earmuff showed no significant difference in localization speed than any other listening condition in the main and interaction effects of HPDs (see Figures 40 and 53).
Clearly, higher localization response times reflected the amount of confusion associated with the customized diotic earmuff in deciding the direction of the approaching backup alarm signal. Again, the lack of any significant difference in localization speed between the Bilsom passive and dichotic earmuffs in the main and interaction effects did not justify their added cost and maintenance (e.g., battery) requirements for the dichotic device, at least for workers with normal hearing.

So far, the discussion of the results of this study provides no support for the first and fifth hypotheses as stated on pages 52 and 53. However, it strongly supports the second hypothesis which stated “Among all HPDs that tested in this study, the diotic earmuff will provide the least accurate and the slowest sound localization decisions in the azimuth dimension”.

**Conclusions Regarding Background Noise Level**

The main effect of pink noise high level (i.e., 90 dBA) on all dependent measures was clearly detrimental. The amount of this detriment was 27% in correct localization, 8% in right-left localization errors, 10% in front-rear localization errors, 18° in localization absolute deviation, and 6 seconds in localization response time (see Figures 41, 42, 43, 44, and 45). As shown in Figure 41, listeners were able to localize correctly 81.4% of the backup alarm sources at 60 dBA whereas they correctly localized only about half of the sources at 90 dBA. Again, this evidenced the detrimental effect of high background noise levels, typical of road construction, on localization accuracy. Also, right-left and front-rear errors, in addition to the localization absolute deviation from the backup alarm direction and the localization response time, more than doubled in percentage when background noise level was increased from 60 to 90 dBA. These results support the
fourth hypothesis which stated “The high background noise level will result in less accurate and slower sound localization decisions in the azimuth dimension than the low background noise level”.

**Conclusions Regarding Backup Alarm Signal Type**

As shown from the main effect of the type of backup alarm signal on localization performance, the spectrally-modified backup alarm provided statistically-significant, though numerically small, advantages over the standard backup alarm. These advantages included a 4% increment in percentage correct localization (Figure 46), 4% decrement in the right-left localization errors (Figure 47), 5° decrement in the localization absolute deviation (Figure 48), and 0.5 second decrement in localization response time (Figure 49). These small improvements in accuracy and response time may save workers’ lives, especially if the surrounding vehicles are backing at high speeds. For instance, the 0.5 second improvement associated with the spectrally-modified backup alarm corresponds to a 7.4 ft advantage for the spectrally-modified backup alarm over the standard backup alarm for a vehicle backing at 10 mph. Clearly, this will provide more opportunity for the construction worker to evade the backing vehicle if he/she was listening to the spectrally-modified backup alarm signal.

The benefit of the spectrally-modified backup alarm was also revealed by the interaction effect between the background noise and the backup alarm signal. When the background noise level increased from 60 to 90 dBA, listeners’ right-left and front-rear confusions increased significantly when they were listening to the standard backup alarm signal. This significant increase in right-left and front-rear confusions did not occur
when they were listening for the spectrally-modified backup alarm signal. Also, the improvements provided by the spectrally-modified backup alarm signal over the standard alarm at 90 dBA were numerically greater than those provided at 60 dBA. Although of small magnitude and statistically nonsignificant, these improvements were consistent across three dependent measures: percentage of right-left localization errors, percentage of front-rear localization errors, and absolute deviation from the actual direction of the backup alarm signal. By further manipulation of the backup alarm signal, both spectrally and otherwise, these improvements at each background noise level could be increased and become statistically-significant.

More benefits of the spectrally-modified backup alarm signal were revealed by the behavior of each hearing protector across the two backup alarm types. The Moldex foam earplug and the Bilsom dichotic earmuff, both at the low end of HPD localization performance on most measures, tended to realize these benefits more than any other HPD. These benefits were in the form of improvements in percentage correct localization (i.e., 10.2% increment for the Bilsom dichotic earmuff and 8.8% increment for the Moldex foam earplug), in percentage of right-left localization errors (i.e., 6.6% decrement for the Bilsom dichotic earmuff and 9.7% decrement for the Moldex foam earplug), and in localization absolute deviation in degrees (i.e., 10.7% decrement for the Bilsom dichotic earmuff and 10.4% decrement for the Moldex SparkPlug\textsuperscript{TM} earplug) (see Figures 54, 55, and 56).

It is obvious from the aforementioned benefits of the spectrally-modified backup alarm signal that adding 400 Hz and 4000 Hz to the standard backup alarm signal
(which peaks at about 1000, 1250, and 3150 Hz) is beneficial for improving the localization accuracy of listeners with normal hearing.

These advantages of the spectrally-modified backup alarm support the third hypothesis of the research, namely that: “The modified backup alarm signal will provide more accurate and quicker sound localization decisions in the azimuth dimension than the standard backup alarm signal”.
RECOMMENDATIONS FOR APPLICATION OF THE RESULTS:

FIRST EXPERIMENT

(Localizing Backup Alarm Signal in Azimuth Dimension)

The first (localization) experiment was a complex factorial experiment with five dependent measures of localization performance inclusive of angular accuracy and response time. This experiment delivered valid results which may be applicable to industrial and construction settings, albeit with some limitations. The revealed disruptive effect of the customized diotic earmuff on normal-hearing listeners' localization performance in this study warrants clear advice to safety professionals. Clearly, if the safety of on-foot workers depends on their attentiveness to the directional sources of acoustic warning signals in their surroundings, then this type of earmuff should not be provided to protect their hearing.

Workers remove hearing protectors for many reasons including discomfort and their inability to detect and localize workplace auditory warning signals. In this study, the lack of any differences in localization performance between most of the tested hearing protectors and the unoccluded ear under many of the experimental conditions negates these excuses, at least from a localization standpoint.

Although the E-A-R/3M HiFi™ earplug showed no advantage over other listening conditions in the main HPD effect, it was advantageous over some of the tested HPDs in the HPD and background noise level interaction effect (Figure 50). In addition, listeners were more confident in their localization decisions when they were fitted with the E-A-R/3M HiFi™ earplug than when they were fitted with the Moldex foam earplug,
the E-A-R/3M UltraFit™ earplug, the Bilsom passive earmuff, and the diotic earmuff. Given that most industrial sites, more than 90%, are exposed to noise less than or equal to 95 dBA (Berger, 2003), the E-A-R/3M HiFi™ earplug with its moderate attenuation (NRR=12) is recommended for use in these sites since it will provide enough attenuation as well as uncompromised sound localization performance.

As indicated by the resultant data, high noise levels adversely affect localization performance, and this is an important consideration. Safety professionals should work to reduce noise levels where it is feasible, not only to protect workers’ hearing, but also to improve their ability to localize warning signals (e.g., backup alarms) accurately and quickly as demonstrated herein. This is very important to avoid any injuries or fatalities, especially where workers must react to vehicles backing at high speeds.

Finally, this research provides important evidence that augmenting standard backup alarms by adding frequency components, which are advantageous in terms of sound localization, improves the directional hearing of listeners to those alarms. Consequently, backup alarm industrial design standards should be revised based on these findings, to include frequency components that foster sound localization by invoking ITDs and ILDs.
RECOMMENDATIONS FOR FUTURE RESEARCH: FIRST EXPERIMENT

(Localizing Backup Alarm Signal in Azimuth Dimension)

In this research, the similarity in localization performance between the dichotic earmuffs and passive earmuffs gives rise to a need for more research on the design of the dichotic earmuffs (or even sound transmission earplugs) such that they provide better directional hearing and signal detection than their passive counterparts.

In terms of hearing acuity, workers in industry and construction can be loosely categorized as workers with normal hearing and those with impaired hearing. Since all the participants who participated in this research had normal hearing, more research is needed to test how listeners with impaired hearing will localize backup alarms.

Finally, this research provided important evidence that the backup alarm signal can be simply and easily improved by spectral modification, yielding small but significant improvements in localization performance, as measured both in accuracy and speed. This research intentionally modified only one parameter of the backup alarm, adding 400 Hz and 4000 Hz to the standard backup alarm spectrum. Given the improvements resulting from this small spectral change, further research is now needed on the spectral details of backup alarms as well as possible changes in the temporal domain (e.g., the “beep rate”), or even other acoustic parameters.
METHODOLOGY: SECOND EXPERIMENT

(Detection Distance of Backup Alarm Signal)

Experimental Design

To assess the participants’ performance in detecting a stationary backup alarm signal and quantifying the linear distance at detection point, an 8×2 completely within-subjects experiment was adopted with two independent variables (Figure 62). The independent variables were: the hearing protection (or open ear) condition (8 levels) and the type of backup alarm signal (2 levels). A discussion of each of the independent variables is provided below.

Independent Variables

Hearing protection condition variable. The hearing protection condition consisted of: 1) unoccluded (i.e., no HPD) condition, 2) Etymotic EB-15 active sound transmission BlastPLG™ earplug set to Lo gain position, 3) Etymotic EB-15 active sound transmission BlastPLG™ earplug set to Hi gain position, 4) E-A-R/3M Combat Arms™ earplug-passive steady state, 5) E-A-R/3M Combat Arms™ earplug-nonlinear, level-dependent state (sometimes called “open”), 6) E-A-R/3M HiFi™ earplug, also marketed as the Etymotic ER-20™ earplug (a “flat” attenuation device), 7) Bilsom Leightning™ Hi-Visibility L3HV passive earmuff, and 8) Bilsom Impact™ dichotic sound transmission earmuff. The HPDs numbered 6, 7, and 8 were the same devices as described previously for the First Experiment on localization discussed herein.
**Figure 62.** Experimental design block diagram for the second (detection distance) experiment.
The rationale for selecting each HPD for this experiment was the same as the one provided for the first experiment, in those instances where the devices were the same. Where not, the following explanation applies.

The EB-15 earplug (see Figures 63a and 63b) has a two-position switch (Lo and Hi) and was evaluated at both of its gain settings. The gain functional profiles, provided by Etymotic Research Inc., appear in Figures 64 and 65. At the “Lo” position, the earplug attenuates loud sounds by approximately 15 dB and protects from impulse sounds while allowing soft sounds to pass through. This is considered beneficial in specific industrial environments where intermittent noise that has primarily impulsive components is prevalent (e.g., construction industry). Also, it allows the workers to communicate during quiet periods. At the “Hi” position, the earplug allows loud sounds to pass through, protects from impulsive sounds by abruptly retarding the gain, and amplifies soft sounds by about 15 dB. Because it provides 15 dB gain during quiet conditions, the EB-15 Hi has the potential to facilitate communications between workers.

The two-state, rocker switch-operated E-A-R/3M Combat Arms™ earplug (see Figures 63c and 63d) in its third generation was selected since its level-dependent state (NRR = 7, see Appendix E) provides low attenuation at low surrounding sound levels, while providing higher attenuation for impulsive noises; thus it is a nonlinear or level-dependent HPD in its open position. However, even in its open position it provides significant attenuation of 18.7 dB at 1000 Hz and higher attenuation with increasing frequency. This earplug may be beneficial in certain industrial environments where intermittent noise is prevalent (e.g., construction industry). When the rocker switch of
the Combat Arms™ is closed, the plug is in its steady state (NRR = 23, see Appendix E) provides a constant protection against continuous sounds. The Combat Arms™ rocker switch design is essentially a further (third generation) development of the same level-dependent technology as in the E-A-R/3M Arc™ earplug used in the First Experiment.

The E-A-R/3M HiFi™ (Etymotic ER-20™) earplug, the Bilsom Leightning™ Hi-Visibility L3HV passive earmuff, and the Bilsom Impact™ dichotic sound transmission earmuff were selected for the same reasons explained in the First (localization) Experiment.

**Backup alarm signal variable.** The second independent variable investigated in this study was the type of the backup alarm signal. The participants’ performance in judging the detection distance of the backup alarm signal was assessed under a standard narrowband backup alarm (Preco Model-6003) and a commercially-available broadband backup alarm. The broadband backup alarm (Brigade Model BSS-97), a product of the Brigade company, is claimed by Brigade to provide better horizontal localization performance, being a “noiseless” (Brigade Electronics, 2008, p.1) backup alarm signal, and travels shorter distances than tonal backup alarm signals, to reduce annoyance for nearby communities. The spectrum for each 97 dBA backup alarm signal is shown in Figure 66. The on-off pulse rate of the backup alarms was 70 pulses per minute for the standard and 80 pulses per minute for the broadband.
Figure 63. HPDs included in the second (detection distance) experiment: a) Etymotic EB-15 active sound transmission BlastPLG™ earplug set to Lo gain position, b) Etymotic EB-15 active sound transmission BlastPLG™ earplug set to Hi gain position, c) E-A-R/3M Combat Arms™ earplug-passive steady state, d) E-A-R/3M Combat Arms™ earplug-nonlinear, level-dependent state (sometimes called “open”), e) E-A-R/3M HiFi™ earplug, also marketed as the Etymotic ER-20™ earplug (a “flat” attenuation device), f) Bilsom Leightning™ Hi-Visibility L3HV passive earmuff, and g) Bilsom Impact™ dichotic sound transmission earmuff.
Figure 64. The gain functional profile for the EB15 at the “Lo” position (Used with permission of Etymotic, 2011).
Figure 65. The gain functional profile for the EB15 at the “Hi” position (Used with permission of Etymotic, 2011).
Figure 66. Standard (Preco Model-6003) and broadband (Brigade Model BSS-97) backup alarm spectra as measured in an open field over a grassy surface at four feet away from the alarm source with the measurement microphone at four feet off the ground.

Participants

A total of 12 participants (Age range: from 18 to 32 years; Gender: 7 males, 5 females) participated as subjects in the detection distance experiment. All qualifying participants were tested with a Beltone Model 114 pure-tone audiometer and verified to have normal bilateral hearing (i.e., defined as less than or equal to 25 dBHL at 250, 500, 1000, 1500, 2000, 3000, 4000, and 6000 Hz in both ears).
Apparatus

Experimental sound field. A long open field with no substantial barrier obstructions or reflective boundary buildings in the city of Radford, Virginia was used as a testing environment. This provided a 2000 ft long by 50 ft wide unobstructed, grassy field in which all tests were performed. The two backup alarms used in this study, the Brigade broadband backup alarm signal and the Preco narrowband backup alarm signal were both operated at their standard output level of 97 dBA per SAE standard J994-2009. To operate these two backup alarms in the open field, a portable 12-Volt battery was used, and it was fully charged prior to each session. To determine the distance between the point where the signal was detected by the participant and the source of the backup alarm, a Tooluxe LCD measuring wheel was used.

Ambient noise measurements. A Larson-Davis sound level meter and real time analyzer system, model 824 was used to obtain the sound pressure level at the detection distance (see Appendix F), as well as the field’s ambient A-weighted equivalent-continuous noise level with an averaging time of 15 minutes (L_{Aeq, 15min}). At the middle of the field, the typical ambient level was 52.3 dBA (slow). In addition, the same system was used to obtain the backup alarms’ spectra in the testing field. Interfaced with this meter was a Larson-Davis model 2559 1/2-inch microphone, and the system was calibrated to 94 dBA at 1 kHz using a Quest QC-20 calibrator.

Procedure

Upon arrival, participants began by attending a screening session after they read and signed an informed consent document (see Appendix G). In this session, the condition of the earcanal and tympanum of the participant was checked using an
otoscope, and if normal, his/her hearing levels were determined using the audiometer. Next, the participant was instructed in the procedure of the experiment. In the experimental session, the method of limits, with distance as the physical measurement variable, and threshold detection as the task, was employed to find at which distance the participant could first detect the backup alarms. Under each hearing protection or open ear condition, the participant walked slowly away from the backup alarm signal until the signal was no longer audible (Ascending Trial). The distance from the backup alarm was then recorded. Next, he/she was instructed to move even further away (by about 10 ft), turn around, and begin moving slowly toward the backup alarm signal until the signal was just barely audible (Descending Trial). The distance from the backup alarm was then again recorded. The ascending and descending trials were repeated a total of two times for each HPD condition under each type of backup alarm. Presentation of the two backup alarms was carried out in a random fashion to avoid order effects. Also, the order effect of assigning hearing protection and open ear conditions to each participant was counterbalanced by a repeated-non-identical complete Latin Square.

**Dependent Measures**

One dependent measure was acquired in this study, the detection distance in feet. It was defined as the distance between the actual backup alarm device and the position where the participant detected the backup alarm signal. For each HPD condition under each type of backup alarm, this position was determined by computing an arithmetic mean of the distances at detection point on the ascending and descending portions of the two trials.
RESULTS: SECOND EXPERIMENT
(Detection Distance of Backup Alarm Signal)

Detection Distance Data Reduction and Statistical Analysis

The two pairs of captured ascending and descending trial data for each condition were entered into a Microsoft Excel™ program and averaged for each subject under each HPD and backup alarm conditions. These averaged data were used as data points in the statistical analysis. To show any statistically-significant differences, at an alpha level of 0.05, between the levels of the independent variables, a within-subject Analysis of Variance (ANOVA) was applied. Any significant difference revealed by ANOVA was further analyzed by a Tukey’s Honestly Significant Difference (HSD) test, also at an alpha level of 0.05. The Statistical Analysis Software (SAS) program was used to conduct the ANOVAs and the Statistical Minitab software, in addition to the Microsoft Excel™ program, were used to generate the mean and confidence intervals graphs, with mean values shown on the data bars and 95% confidence limits plotted.

Hearing Protection Device (HPD) Main Effects

For the detection distance in feet, the ANOVA revealed a significant main effect of HPD. The HPD effect on detection distance was highly significant, \( F(7,77) = 45.8, p < 0.0001 \) (see Table 10), with the means ranging from a low (i.e., worst) of 1132.2 ft for the Bilsom passive earmuff to a high (i.e., best) of 1652.3 ft for the unoccluded condition (Figure 67). Post hoc analyses via Tukey’s test indicated that the Bilsom passive earmuff (at 1132.2 ft) was significantly poorer than all other HPDs and the open ear listening condition in detection distance achieved, and that there were no
statistically-significant differences between the unoccluded ear (1652.3 ft), EB-15-Lo BlastPLG™ (1546.2 ft), EB-15-Hi BlastPLG™ (1543.4 ft), E-A-R/3M Combat Arms™ earplug-nonlinear, level-dependent state (1507.8 ft), E-A-R/3M HiFi™ earplug (1497.7 ft), and Bilsom Impact™ dichotic earmuff (1567.2 ft). In addition, the detection distance in feet while using the E-A-R/3M Combat Arms™ earplug-passive steady state differed significantly from only the open ear condition, at 1474.1 ft versus 1652.3 ft for the open ear.

**Backup Alarm Signal (BU) Main Effects**

The backup alarm signals’ significant main effect on the detection distance in feet was revealed via ANOVA. The means were 1600.9 ft for the standard backup alarm signal and 1379.4 ft for the broadband backup alarm signal (Figure 68), with ANOVA statistics of $F(1,11) = 18.8$, $p = 0.0012$ (see Table 10). Clearly, the broadband backup alarm was at a very long 221.5 ft disadvantage in distance-at-detection.

**Table 10.** 
*ANOVA Summary table for the detection distance in feet (bold text indicates significance at $p \leq 0.05$).*

<table>
<thead>
<tr>
<th>Source*</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>$F**$</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPD</td>
<td>7</td>
<td>4007152.0</td>
<td>572450.3</td>
<td>45.8</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>HPD×S</td>
<td>77</td>
<td>962978.1</td>
<td>12506.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BU</td>
<td>1</td>
<td>2354655.8</td>
<td>2354655.8</td>
<td>18.8</td>
<td>0.0012</td>
</tr>
<tr>
<td>BU×S</td>
<td>11</td>
<td>1374473.0</td>
<td>124952.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HPD×BU</td>
<td>7</td>
<td>35062.3</td>
<td>5008.9</td>
<td>0.5</td>
<td>0.8207</td>
</tr>
<tr>
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<td>77</td>
<td>749109.8</td>
<td>9728.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*HPD = Hearing Protection Device, BU = Backup Alarm, S = Subjects.  
**Each $F$-ratio consists of the source of variance under test in the same row, divided by the error term for that source in the immediately following row.
Figure 67. Main effect of HPDs on detection distance in feet, with mean values shown on bars with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$) according to Tukey’s test.
Figure 68. Main effect of backup alarm type on detection distance in feet, with mean values shown on bars with 95% confidence intervals plotted. Means with the same letter are not significantly different ($p \leq 0.05$).
DISCUSSIONS AND CONCLUSIONS: SECOND EXPERIMENT

(Detection Distance of Backup Alarm Signal)

Conclusions Regarding HPDs and Detection Distance

For on-ground workers, it is crucial to detect backup alarm signals as far away as possible rather than at close distances since this will provide them more time to react to approaching vehicles. The main objective for this experiment was to investigate how the distance where the backup alarm signal can be detected (i.e., operationally termed ‘distance-at-detection’ or ‘detection distance’) in a free field is affected by the various HPDs versus the open ear. The significant differences found between certain HPDs have demonstrated that the choice of a hearing protector can influence this detection distance. As shown in Figure 67, the E-A-R/3M Combat Arms™ earplug-passive steady state and the Bilsom passive earmuff were the only devices to significantly degrade the detection distance when compared to that of the unoccluded ear condition. On the other hand, there was no difference between the other tested HPDs, or between any of them and the unoccluded ear condition. These results suggest that the selection of the E-A-R/3M Combat Arms™ earplug-passive steady state and the Bilsom passive earmuff by construction site safety professionals should be made with serious precaution.

Conclusions Regarding Backup Alarm Signal Type and Detection Distance

The main effects of the type of backup alarm signal demonstrated a statistically-significant advantage of the standard backup alarm over the broadband backup alarm on detection distance in feet. The magnitude of the improvement produced by the standard backup alarm over the Brigade™ alarm was 221.5 feet, a
very large margin. Such a large deficit in detection distance under the Brigade broadband alarm gives rise to the need for caution in its selection for work environments that include construction vehicles, and particularly for those with high reversing speeds. For instance, for a vehicle backing at 10 mph (a rubber-tire loader, for example), the 221.5 ft decrease in detection distance equates to the vehicle arriving 15 seconds sooner at the worker from the point at which its alarm was first heard. It should be obvious that on-ground construction workers have more distance, and thus more time, to react to approaching vehicles when a standard backup alarm is installed on construction site vehicles than would workers at a site where a broadband backup alarm is being used.

Post-Hoc Correlation Analysis: Backup Alarm versus Attenuation Spectra

As shown in Figure 67, the Bilsom passive earmuff provided the minimum (i.e., worst) detection distance. This was believed to be due to its high attenuation characteristics compared to other HPDs used in the detection distance experiment. To draw a general conclusion about the relationship between the amount of an HPD’s attenuation and the detection distance, backup alarm levels at listeners’ earcanals (i.e., the difference between the backup alarm level and the amount of attenuation, see Figures 69 and 70) at the following frequencies: 500, 1000, 2000, 3150, 4000, and 6300 Hz were correlated against the detection distance for the four tested passive HPDs (E-A-R/3M Combat Arms™ earplug-passive steady state, E-A-R/3M Combat Arms™ earplug-nonlinear, level-dependent state, E-A-R/3M HiFi™ earplug, and Bilsom Leightning™ Hi-Visibility L3HV passive earmuff). The Etymotic EB-15 active sound transmission BlastPLG™ earplug and the Bilsom Impact™ dichotic sound transmission
earmuff were not considered in this correlation analysis since they were set at their gain positions where they provided essentially no attenuation at the low sound levels present in the experiment.

By using the parametric Pearson correlation test, the correlation between the standard backup alarm’s levels at the listeners’ ear position and the detection distance was strong, positive, and significant \((r = 0.6 \text{ and } p = 0.003)\). Also, the Pearson correlation test revealed a strong, positive, and significant correlation \((r = 0.5 \text{ and } p = 0.015)\) between the broadband backup alarm’s levels in the listeners’ ear canals and the detection distance. Since human hearing is most sensitive in the 1000 - 4000 Hz frequency region, and since the standard backup alarm has dominant energy in the range of 1250 to 4000 Hz, another correlation test was applied on only 1000, 2000, 3150, and 4000 Hz. The Pearson test revealed a strong, positive, and significant correlation \((r = 0.5 \text{ and } p = 0.038)\) between the standard backup alarm’s levels at the listeners’ position and the detection distance. In addition, it revealed a strong, positive, and significant correlation \((r = 0.6 \text{ and } p = 0.008)\) between the broadband backup alarm’s levels in the listeners’ ear canals and the detection distance. These results partially supported the conclusion that as the amount of HPD attenuation increases, the detection distance decreases as well. As depicted in Figures 69 and 70, passive HPDs which had high attenuation (i.e., the E-A-R/3M Combat Arms™ earplug-passive steady state, and the Bilsom Leightning™ Hi-Visibility L3HV passive earmuff) provided lower (i.e., worse) detection distance than the ones with low attenuation (i.e., E-A-R/3M Combat Arms™ earplug-nonlinear, level-dependent state, E-A-R/3M HiFi™ earplug).
Figure 69. Attenuation profile for the passive HPDs tested in the second (detection distance) experiment versus the spectrum of the standard backup alarm. A significant, $p \leq 0.05$, correlation between the difference between the backup alarm level and the amount of attenuation and the detection distance is depicted by Pearson correlation coefficient ($r$). The detection distance mean in feet is shown for each passive HPD for the standard backup alarm. (See text for details on correlation analysis).
Figure 70. Attenuation profile for the passive HPDs tested in the second (detection distance) experiment versus the spectrum of the broadband backup alarm. A significant, $p \leq 0.05$, correlation between the difference between the backup alarm level and the amount of attenuation and the detection distance is depicted by Pearson correlation coefficient ($r$). The detection distance mean in feet is shown for each passive HPD for the broadband backup alarm. (See text for details on correlation analysis)
RECOMMENDATIONS FOR APPLICATION OF THE RESULTS:

SECOND EXPERIMENT

(Detection Distance of Backup Alarm Signal)

The research was comprised of a dual variable, complete factorial experiment with one dependent measure of detection distance performance. Based on the statistical analyses of the resultant data, it is clear that there are differences in normal-hearing listeners’ detection distance performance that depends upon both HPD type/design and backup alarm spectral content. It must also be kept in mind that the dBA level of the alarms was not a factor since it was a constant 97 dBA for both alarms in accordance with the SAE J994-2009 standard.

The results of this study partially suggest that as the attenuation of the hearing protectors increases, certain precautions should be considered by the construction sites’ safety professionals. This is because, as it was the case with the Bilsom passive earmuff and E-A-R/3M Combat Arms™ earplug-passive steady state, high attenuation significantly reduces the detection distance, and as a result, on-foot workers will have less time to react to any approaching vehicle.

Also, the results showed an advantage of the standard (narrowband) backup alarm signal over the broadband backup alarm signal in terms of detection distance. The broadband Brigade™ backup alarm manufacturer claims that its alarm is advantageous in providing better horizontal localization performance, being a “noiseless” backup alarm signal, and traveling shorter distances than tonal backup alarm signals to reduce annoyance. Although in certain situations, the priority maybe to
provide “noiseless” and localizable warning alarms, in most construction sites, the priority must be to provide an increased envelope of safety for on-foot workers via an alarm which is detectable over long enough distances to afford adequate evasion time. The results of this study showed that the standard (narrowband) backup alarm signal provides more distance, and therefore more time, for on-foot workers to react to backing vehicles compared to the broadband backup alarm signal. It must be recognized that this conclusion is based on an experiment with specific conditions, and thus the results may not be generalizable to other backup alarm signals, or to other HPDs.
RECOMMENDATIONS FOR FUTURE RESEARCH: SECOND EXPERIMENT

(Detection Distance of Backup Alarm Signal)

More research is needed on the effect of other variables that exist in construction sites (e.g., noises in road construction) on detection distance. Although the effects of hearing protectors and background noises on backup alarm signal detection was investigated in the literature (i.e., Casali, Robinson, Dabney, & Gauger, 2004), including the effect of the background noise in addition to the effect of hearing protectors on the detection distance is needed and will provide more valid results.

In terms of hearing acuity, workers in industry and construction can be categorized as workers with normal hearing and those with impaired hearing. Since all the participants who participated in this study had normal hearing, more research is needed to determine how listeners with impaired hearing will perform in detection distance tasks.
RECOMMENDATIONS FOR DISSEMINATIONS OF RESULTS

TO VARIOUS GROUPS

The author recommends that the following agencies and other entities may benefit from the findings of the two experiments comprising this dissertation.

1. Society of Automotive Engineers (SAE) backup/forward alarm subcommittee of the SAE construction and agricultural sound level committee. SAE J994 and SAE J1446.

2. The Center for Construction Research and Training, formerly known as the Center to Protect Workers’ Rights (CPWR).


4. Hearing protection device (HPD) manufacturers.

5. Backup alarm manufacturers.
REFERENCES


34.


APPENDIX A - HPDs Attenuation Data - First (Localization)

Experiment
<table>
<thead>
<tr>
<th>HPD*</th>
<th>NRR**</th>
<th>Octave Band Attenuation Data (dB)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Test Frequency (Hz)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>125</td>
</tr>
<tr>
<td>HPD2</td>
<td>33</td>
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<td></td>
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<td>HPD5a</td>
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<tr>
<td></td>
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<td>23</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
</tr>
</tbody>
</table>

*HPD = Hearing Protection Device
**NRR = Noise Reduction Rating

HPD2 = Moldex Model-6604 foam passive earplug (SparkPlug™ earplug)
HPD3 = E-A-R/3M Ulrafit™ premolded passive earplug
HPD4 = E-A-R/3M HiFi™ earplug (a uniform or “flat” attenuation HPD)
HPD5a = E-A-R/3M Arc™ earplug (level-dependent side)
HPD5b = E-A-R/3M Arc™ earplug (steady-state side)
HPD6 = Bilsom Leightning™ L3HV passive earmuff
HPD7 = Custom-made diotic electronic sound transmission earmuff
HPD8 = Bilsom Impact™ dichotic electronic sound transmission earmuff
APPENDIX B - Backup Alarm Signal Simulation - First

(Localization) Experiment
The backup alarm signal used in the first (localization) experiment was simulated as an approaching signal towards the listener. This simulation was performed by increasing the sound pressure level of the backup alarm signal. Since the backup alarm signal is a pulsating signal in nature, each pulse of the approaching signal corresponds to a distance away from the listener. To find the maximum sound pressure level (closest distance to the listener), the following approach was adopted.

To react to any approaching backing vehicle, listeners need time to attend (t<sub>attend</sub>) to the backup alarm signal (i.e., detect and recognize), to localize it (t<sub>localize</sub>), and to move across the backing vehicle width (t<sub>cross</sub>). The summation of these times should be less than the times lapsed between the instance where the backing vehicle starts backing and the instance where it strikes the listener (t<sub>strike</sub>). The following equation represents the above mathematically:

\[
\begin{align*}
t_{\text{attend}} + t_{\text{localize}} + t_{\text{cross}} &< t_{\text{strike}} \\
\Rightarrow t_{\text{attend}} + t_{\text{localize}} + \frac{W}{Jogging\ Speed} &< \frac{d}{BS} \\
\Rightarrow d &> BS \times \left( t_{\text{attend}} + t_{\text{localize}} + \frac{W}{Jogging\ Speed} \right) \quad \text{.................................}[1]
\end{align*}
\]

where

- \(d\) = the distance from the backing vehicle to the listener
- \(W\) = backing vehicle width
- \(BS\) = backing vehicle speed
- Jogging Speed = human average jogging speed

If the listener has been already attended to and localizes the backup alarm signal, then equation [1] becomes:

\[
\begin{align*}
\Rightarrow d &> BS \times \left( \frac{W}{Jogging\ Speed} \right) \quad \text{.................................}[2]
\end{align*}
\]

A backing speed (BS) of 10 mph was chosen since it represents one of the fastest backing speeds (J. G. Casali, personal communication, 2007). In regards to the backing vehicle width (W), a width of 11 ft was chosen since it represents one of the widest construction vehicles’ widths available in the marker. It is the width of one of the John Deere 4WD Loaders, model-844K (John Deere, 2011). By substituting these values with the average human Jogging Speed of 6 mph (Siljander, 2008) in equation
[2], the minimum distance separating the listener in the first (localization) experiment from the backup alarm device (d) should be greater than 18 ft. A 19 ft was chosen.

After the closest distance of 19 ft was determined, the other distances at which the backup alarm signal pulsed determined as follows. Since the backing speed is 10 mph (14.67 ft/s) and the pulsating rate for the backup alarm signal is 1 pulse per second, then the backup alarm beeps for 7.333 ft and then silence for the consecutive 7.333 ft. Based on this, the backup alarm signal was considered to beeps at every increment of 7.333 ft above 19 ft, see the table at the bottom of this appendix.

To calculate the sound pressure level of the backup alarm signal at the listener position, two mechanisms, geometrical divergence and ground reflections, among others (e.g., wind effect and air absorption) which affect the propagation of sound waves was considered (Daigle & Piercy, 1998). The following figure depicts some of the terms which will appear in the following equations:

In this figure, the backup alarm represents the source of the sound (s) and the depicted human represent the receiver of the backup alarm signal (r). The symbols in this figure represent:

\[ R_1 = \text{the distance between the source of the backup alarm signal and a close point} \]
\[ R_2 = \text{the distance between the source of the backup alarm signal and the receiver} \]
\[ h_s = \text{the height of the source of the backup alarm signal} \]
\[ h_r = \text{the height of the receiver} \]

by considering only the geometrical divergence and ground reflections on the propagation of the backup alarm signal, the total attenuation at distance R can be calculated as follows (Daigle & Piercy, 1998):

\[ A_{\text{total}} = L_w - L_p = A_{\text{div}} + A_{\text{ground}} \]  \[\text{[3]}\]

where

\[ L_p = \text{sound pressure level at distance R, dB} \]
\[ L_w = \text{sound power level of the sound source, dB} \]
\[ A_{\text{total}} = \text{total attenuation, dB} \]
$A_{\text{div}} = \text{geometric divergence attenuation} = 20 \log_{10} R + 0.6 - C \quad \text{dB}$

$A_{\text{ground}} = \text{ground attenuation, dB}$

$C = \text{constant, dB}$

Based on the chapter entitled by “BACKUP ALARMS IN CONSTRUCTION INDUSTRY”, the sound pressure level associated with any type of backup alarms is the one measured at 4 ft away from the source of the backup alarm signal. This was used in the calculations as follows:

At $R_1$, the total attenuation is:

$L_{w1} - L_{p1} = A_{\text{div}1} + A_{\text{ground}1}$

$L_{w} - L_{p1} = [20 \log_{10} R_1 - 0.6 + C] + A_{\text{ground}1} \quad \text{[4]}$

At $R_2$, the total attenuation is:

$L_{w2} - L_{p2} = A_{\text{div}2} + A_{\text{ground}2}$

$L_{w} - L_{p2} = [20 \log_{10} R_2 - 0.6 + C] + A_{\text{ground}2} \quad \text{[5]}$

Note that $L_{w1} = L_{w2} = L_{w}$ since the sound emitted from the same source.


$\rightarrow L_{p2} - L_{p1} = 20 \log_{10} (R_1/R_2) + A_{\text{ground}1} - A_{\text{ground}2}$

$\rightarrow L_{p2} = L_{p1} + 20 \log_{10} (R_1/R_2) + A_{\text{ground}1} - A_{\text{ground}2} \quad \text{[6]}$

In the first localization experiment, type B of backup alarms was selected. The sound pressure level of the backup alarm signal at 4 ft away from the backup alarm is 107 dBA. As a result, equation [6] becomes

$L_{p2} = 107 + 20 \log_{10} (4/R_2) + A_{\text{ground}1} - A_{\text{ground}2} \quad \text{[7]}$

The ground attenuations were calculated by using the procedure explained by Daigle & Piercy (1998). Using this procedure, three components should be assessed: 1) $G = \text{constant}$. This constant depends on the type of the ground. It equals 0 for hard surfaces and 1 for porous surfaces. In this research, a value of 0.5 which was believed to represents the ground in the earth-moving construction sites was chosen. 2) $h_r = \text{the receiver height} = 3.875 \text{ ft}$. This height was chosen since it is the same as the height of the seated-listener in the first (localization) experiment. 3) $h_s = \text{the source height} = 3.5 \text{ ft}$.

Although the procedure adopted recommends calculating the ground attenuation at each octave band, only the ground attenuation at 1000 Hz was considered in this research since most of the standard backup alarm energy was located around this frequency.
Substituting the calculated ground attenuations in equation [7], the sound pressure level of the backup alarm signal at distances with an increment of 7.333 ft from 19 ft to 239 ft, is shown in the following table.

<table>
<thead>
<tr>
<th>Distance away from the Listener (ft)</th>
<th>Sound Pressure Level (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>95</td>
</tr>
<tr>
<td>34</td>
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<tr>
<td>224</td>
<td>72</td>
</tr>
<tr>
<td>239</td>
<td>72</td>
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</table>
APPENDIX C - Informed Consent Form - First (Localization)

Experiment
Informed Consent for Participants of Investigative Projects

Title of Project: Azimuthal Sound Localization and Distance Perception under Electronic and Non-Electronic Hearing Protection Devices in Noisy Environments

Principal Investigators: Khaled Alali, Graduate Student, ISE

Faculty Advisor: John G. Casali, Ph.D., Grado Professor, ISE

I. THE PURPOSE OF THIS RESEARCH

You are invited to participate in a research study aimed at determining your ability to localize two types of backup alarm signals within background noise in either unoccluded condition (ears uncovered), or when wearing different types of hearing protection devices (HPDs). A total of 12 participants will be recruited for this experiment, with separate experimental sessions scheduled for each participant.

II. PROCEDURES

The procedures to be used in this research are as follows. If you wish to become a participant after reading the description of the study, then sign this form. This study requires your participation in five separate experimental sessions, including the initial screening and familiarization session. First, you will be screened to determine if you qualify for the study. 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. Then, you will be given an examination in which the experimenter will look into your ears using an otoscope to determine the condition of your ears. Next, your right and left ear hearing will 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 seven hearing protectors to be used in the study to ensure that they fit you properly. These hearing protectors include four earplugs and three earmuffs.

If you qualify and choose to continue, the screening session will conclude with a practice/training session of the localization experimental task. To do so, you will be seated in a chair in a quiet room with your ears uncovered (unoccluded). Arranged around your chair in a
circle are small loudspeakers. A table in front of you will have a tablet laptop PC that you will use to declare your responses, as well as a button that is labeled ‘stop.’ Your task is to determine from which loudspeaker you think the backup alarm is coming from. As soon as you decide from where the backup alarm signal seems to be coming from, press the ‘stop’ button on your desk. The tablet laptop PC has a circular dial on it. Choose the location on the circular dial that corresponds to the location from where you thought you heard the backup alarm signal by pressing it with the stylus. To meet the familiarization criteria, you should achieve at least 50% correct localization responses out of your total responses. The initial screening and familiarization session will last for approximately 30 minutes.

Localization Experiment

The localization experimental sessions, of which there are four, 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. The experimenter will then fit the hearing protector to be used in that session on you and will ensure a proper fit for the device (note that for one session, your ears will be unoccluded). In the first experimental session, you will be seated in the middle of a circle formed by small loudspeakers equally spaced from each other. Arranged behind these small loudspeakers are four, larger loudspeakers that will present background noise in the form of ‘pink noise’ (this is a flat-by-octaves sound, similar to static noise, but somewhat deeper in pitch). In front of you is a table with a tablet PC and a pushbutton, and on the wall behind it is a digital timer. On the tablet PC’s screen, you will see a circle that represents the circle of speakers that are around you. At the start of the experimental trial, the experimenter will present one of two background noises (either 60 dBA or 90 dBA pink noise) through the larger loudspeakers, and will then begin presenting the backup alarm signal for which you will be listening from the small loudspeakers in the circle around you (as discussed previously). (During the experimental trials, the experimenter will be seated outside your field of view) The backup alarm signal will be presented to you through one of the small loudspeakers as a simulated approaching signal (that is, approaching your seated position). This simulation will be carried out by increasing the backup alarm signal level from 72 dBA to 99 dBA at its furthest and closest simulated distance from you, respectively. Once you feel that the backup alarm signal is clearly audible to you, and you are confident about its source, you should depress the pushbutton on your desk, which will stop the digital timer. You should then use the tablet PC’s mouse to indicate where on the PC’s circle you think the signal was emanating. You should respond as fast as you can, but you will be given 15.5 seconds to make your decision once the trial begins. The aforementioned procedure constitutes one experimental trial. Each trial will be repeated one more time, for a total of two trials. To avoid fatiguing you, only two hearing protection conditions will be conducted during each experimental session, which should last about 1 hour. At the end of each experimental session including the use of hearing protection device, you will be given a one page comfort evaluation form for the used hearing protection device. The other experimental conditions will be tested similarly on different days.

As mentioned above, four experimental sessions will be conducted, and in each session you will experience two hearing protector conditions only, as noted. The two background noise levels that you will be exposed to in the localization experimental sessions are 60 dBA and 90 dBA. The range of the backup alarm signal level that you will be exposed to in the experimental
sessions is 72 dBA to 99 dBA. (Occupational Safety and Health [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. The noise exposures while participating in this study are not sufficient to cause any damage to your hearing, and indeed are well under the dose of noise exposure as prescribed by OSHA. For example, if you were exposed to a backup alarm signal level of 100 dBA for a half-hour—without hearing protection—the noise dose would be 25% [OSHA maximum allowable is a 100% dose]. As such, according to OSHA regulations, you could spend up to two hours in 100 dBA noise before you would be required to wear hearing protection. Thus, the continual exposure at the highest level of the experiment in the ‘worst-case’ condition (i.e., 100 dBA backup alarm signal with an open-ear) of only 10 seconds does not put you at any hearing risk. Similarly, if you were exposed to the highest level of the background noise level in the localization experimental sessions of 90 dBA for a half-hour—without hearing protection—the noise dose would be around 6% [OSHA maximum allowable is a 100% dose]).

III. RISKS

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 90 dBA for 8 hours each day (both of these conditions result in a 100% noise dose). 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 effect of HPDs on localizing backup alarm signals under background noise conditions.

No guarantee of benefits has been made to encourage you to participate. You may also receive a summary of the results of this research when completed. Please leave or send a self addressed envelope if you are interested in the summary. 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 of the research.

VI. COMPENSATION

For participation in this experiment, you will receive a minimum of $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 of this project. These include, but are not limited to, unforeseen health-related difficulties, inability to perform the task, and unforeseen danger to the participant, experimenter, or 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 hearing tests and to follow the experimental session instructions 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 the signature page of 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. Then if you decide to participate, please sign your name on this page and the following pages.
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, and Khaled Alali, a graduate student. They may be contacted at the following address and phone numbers:

Auditory Systems Laboratory Dr. Casali: (540) 231-5073
Room 538 Whittemore Hall Khaled Alali: (540) 257-3199
Virginia Tech
Blacksburg, VA 24061

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

Dr. David Moore, 1880 Pratt Drive, Suite 2006, Virginia Tech, Blacksburg, VA, 24061
Telephone: (540) 231-4991
APPENDIX D - Comfort Rating Scale - First (Localization)

Experiment
HOW DOES THE DEVICE YOU ARE WEARING FEEL NOW?

<table>
<thead>
<tr>
<th>Feeling</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncomfortable</td>
<td>___ : ___ : ___ : ___ : ___ : ___ : ___</td>
</tr>
<tr>
<td>Comfortable</td>
<td></td>
</tr>
<tr>
<td>Painless</td>
<td>___ : ___ : ___ : ___ : ___ : ___ : ___</td>
</tr>
<tr>
<td>Painful</td>
<td></td>
</tr>
<tr>
<td>No Uncomfortable Pressure</td>
<td>___ : ___ : ___ : ___ : ___ : ___ : ___</td>
</tr>
<tr>
<td>Pressure</td>
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</tr>
<tr>
<td>Intolerable</td>
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<tr>
<td>Loose</td>
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<tr>
<td>Not Bothersome</td>
<td>___ : ___ : ___ : ___ : ___ : ___ : ___</td>
</tr>
<tr>
<td>Bothersome</td>
<td></td>
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<tr>
<td>Heavy</td>
<td>___ : ___ : ___ : ___ : ___ : ___ : ___</td>
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<tr>
<td>Light</td>
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<tr>
<td>Cumbersome</td>
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</tr>
<tr>
<td>Not Cumbersome</td>
<td></td>
</tr>
<tr>
<td>Hard</td>
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<tr>
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<td>___ : ___ : ___ : ___ : ___ : ___ : ___</td>
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<tr>
<td>Hot</td>
<td></td>
</tr>
<tr>
<td>Smooth</td>
<td>___ : ___ : ___ : ___ : ___ : ___ : ___</td>
</tr>
<tr>
<td>Rough</td>
<td></td>
</tr>
<tr>
<td>No Feeling of Isolation</td>
<td></td>
</tr>
<tr>
<td>Ear Open</td>
<td>___ : ___ : ___ : ___ : ___ : ___ : ___</td>
</tr>
<tr>
<td>Ear Blocked</td>
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</tr>
<tr>
<td>Ear Empty</td>
<td>___ : ___ : ___ : ___ : ___ : ___ : ___</td>
</tr>
<tr>
<td>Ear Full</td>
<td></td>
</tr>
<tr>
<td>Confident Sound Localization</td>
<td>___ : ___ : ___ : ___ : ___ : ___ : ___</td>
</tr>
</tbody>
</table>
APPENDIX E - HPDs Attenuation Data - Second (Detection Distance) Experiment
<table>
<thead>
<tr>
<th>HPD*</th>
<th>NRR**</th>
<th>Octave Band Attenuation Data (dB)</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td>Test Frequency (Hz)</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td>HPD2</td>
<td>25</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
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<td>HPD3</td>
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<td>Mean</td>
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<tr>
<td></td>
<td></td>
<td>SD</td>
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<td>SD</td>
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<td>SD</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>SD</td>
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</tbody>
</table>

*HPD = Hearing Protection Device  
**NRR = Noise Reduction Rating

HPD2 = EB-15-Lo active earplug  
HPD3 = EB-15-Hi active earplug  
HPD4 = E-A-R/3M Combat Arms™ earplug-passive steady state  
HPD5 = E-A-R/3M Combat Arms™ earplug-nonlinear, level dependent state  
HPD6 = E-A-R/3M HiFi™ earplug (a “flat” attenuation device)  
HPD7 = Bilsom Leightning™ Hi-Visibility L3HV passive earmuff  
HPD8 = Bilsom Impact™ dichotic electronic sound transmission earmuff
APPENDIX F - Sound Pressure Level at the Detection Distance - Second (Detection Distance) Experiment
The change in the sound pressure level, in dBA and dBC, for the Standard (Preco Model-6003) and broadband (Brigade Model BSS-97) backup alarm signals across the distance for the distance detection experiment was calculated as follows. First the sound pressure level of the ambient noise alone was measured by using the Larson-Davis sound level meter and real time analyzer system 824. Then while the backup alarm signal was operable, the sound pressure level of both the ambient noise and the backup alarm signal was measured. Measurements were made without any interventions of noise that is not usually exited in the test field. After these measurements, the following equation (Casali, 2006) was used to determine the sound pressure level for the backup alarm signal alone:

$$L_{p1} = 10 \log \left[ \frac{L_p}{10^{10} - 10^{10}} \right]$$

where

- $L_p$ = total sound pressure level of $L_{p1}$ and $L_{p2}$.
- $L_{p1}$ = sound pressure level of the backup alarm signal alone.
- $L_{p2}$ = sound pressure level of the ambient noise alone.

After substituting the measured values of $L_p$ and $L_{p2}$ in the above equation, the resulted values for $L_{p1}$ at different distances away from the backup alarm device is shown in the following tables:

<table>
<thead>
<tr>
<th>Distance in ft</th>
<th>$L_{p2}$</th>
<th>$L_p$ (Standard)</th>
<th>$L_p$ (Broadband)</th>
<th>$L_{p1}$ (Standard)</th>
<th>$L_{p1}$ (Broadband)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>54</td>
<td>94.8</td>
<td>95.4</td>
<td>94.8</td>
<td>95.4</td>
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<td>54.1</td>
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<td>70.9</td>
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<td>59.1</td>
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</tr>
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<td>300</td>
<td>50.7</td>
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<td>55.1</td>
<td>50.3</td>
<td>53.1</td>
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<td>54.1</td>
<td>52.5</td>
<td>51.6</td>
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<td>53.9</td>
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<td>52.5</td>
<td>47.5</td>
<td>48.8</td>
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<td>700</td>
<td>50.2</td>
<td>51.1</td>
<td>52.7</td>
<td>43.8</td>
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<td>47.6</td>
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<td>51.2</td>
<td>45.0</td>
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</table>
### Sound Pressure Level in dBC

<table>
<thead>
<tr>
<th>Distance in ft</th>
<th>( L_{p2} ) (Standard)</th>
<th>( L_p ) (Standard)</th>
<th>( L_{p1} ) (Standard)</th>
<th>( L_{p2} ) (Broadband)</th>
<th>( L_p ) (Broadband)</th>
<th>( L_{p1} ) (Broadband)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>93.9</td>
<td>93.0</td>
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<td></td>
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<tr>
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<td>68.7</td>
<td>71.3</td>
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<td>70.5</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>62.6</td>
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<td>69.5</td>
<td>65.0</td>
<td>68.5</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>60</td>
<td>66.4</td>
<td>69.1</td>
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<td>68.5</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>61</td>
<td>65.5</td>
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<td>63.6</td>
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<tr>
<td>800</td>
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<td>60</td>
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<tr>
<td>900</td>
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<td>61</td>
<td>63.9</td>
<td>54.1</td>
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where

- \( L_{p2} \) = the sound pressure level of the ambient noise
- \( L_p \) (Standard) = the total sound pressure level of the ambient noise and the standard backup alarm signal
- \( L_p \) (Broadband) = the total sound pressure level of the ambient noise and the broadband backup alarm signal
- \( L_{p1} \) (Standard) = the sound pressure level of the standard backup alarm signal alone
- \( L_{p1} \) (Broadband) = the sound pressure level of the broadband backup alarm signal alone
APPENDIX G - Informed Consent Form - Second (Detection Distance) Experiment
Title of Project: Azimuthal Sound Localization and Distance Perception under Electronic and Non-Electronic Hearing Protection Devices in Noisy Environments

Principal Investigators: Khaled Alali, Graduate Student, ISE

Faculty Advisor: John G. Casali, Ph.D., Grado Professor, ISE

I. THE PURPOSE OF THIS RESEARCH

You are invited to participate in a research study aimed at determining your ability to judge the detection distance of two types of backup alarm signals in a free field under either unoccluded conditions (ears uncovered), or when wearing different types of hearing protection devices (HPDs). A total of 12 participants will be recruited for this experiment, with separate experimental sessions scheduled for each participant.

II. PROCEDURES

The procedures to be used in this research are as follows. If you wish to become a participant after reading the description of the study, then sign this form. This study requires your participation in five separate experimental sessions, including the initial screening session. First, you will be screened to determine if you qualify for the study. 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. Then, you will be given an examination in which the experimenter will look into your ears using an otoscope to determine the condition of your ears. Next, your right and left ear hearing will 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 hearing protectors to be used in the study to ensure that they fit you properly.
Distance Perception Experiment

The distance perception experimental sessions, of which there are four, 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. The experimenter will then fit the hearing protector to be used in that session on you and will ensure a proper fit for the device (note that in one session, your ears will be unoccluded). In the first experimental session, you will be standing in a free field and your back towards a backup alarm signal. Your task is to move away from the source of the signal until the signal is no more detectable. After which you will be moving back towards the signal until it is detectable. The experimenter will record the distance from the backup alarm position to the point where the signal is no more detectable and were it is detectable. This procedure will be repeated many times, in the remaining experimental sessions, under different hearing protectors and different backup alarm signals.

III. RISKS

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 effect of HPDs on at what distance can the backup alarm signal be detected in a free field. No guarantee of benefits has been made to encourage you to participate. You may also receive a summary of the results of this research when completed. Please leave or send a self addressed envelope if you are interested in the summary. 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 of the research.
VI. COMPENSATION

For participation in this experiment, you will receive a minimum of $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 of this project. These include, but are not limited to, unforeseen health-related difficulties, inability to perform the task, and unforeseen danger to the participant, experimenter, or 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 hearing tests and to follow the experimental session instructions 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 the signature page of 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. Then if you decide to participate, please sign your name on this page and the following pages. 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.
The research team for this experiment includes Dr. John G. Casali, Director of the Auditory Systems Laboratory, and Khaled Alali, a graduate student. They may be contacted at the following address and phone numbers:

Auditory Systems Laboratory                   Dr. John Casali: (540) 231-5073
Virginia Tech                                      Khaled Alali: (540) 257-3199
Blacksburg, VA 24061

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

Dr. David Moore, 1880 Pratt Drive, Suite 2006, Virginia Tech, Blacksburg, VA, 24061
Telephone: (540) 231-4991
APPENDIX H - One-Page Fact Sheet for the National Occupational Research Agenda (NORA) of NIOSH
Fact Sheet for the Selection of Backup Alarms and Hearing Protection Devices in Construction Industry

Due to their design, many construction vehicles and mobile equipment (e.g., backhoes, loaders, excavators, dump trucks, etc.) have an obstructed rear view which makes it difficult for drivers to view the area behind their vehicles to insure it is free of on-foot workers. For this reason, backup (i.e., reverse) alarms are used to warn on-foot construction workers of the danger imposed by backing construction vehicles and mobile equipment. The use of these alarms is common in general industry as well as in construction and has been since the 1970’s.

OSHA Regulations for Backup Alarm Use in Construction Industry

OSHA has two standards that have bearing on the use of backup alarms on construction motor vehicles and moving machines. For construction motor vehicles, OSHA standard number 1926.601 states, “No employer shall use any motor vehicle equipment having an obstructed view to the rear unless: (b)(4)(i) The vehicle has a reverse signal alarm audible above the surrounding noise level or: (b)(4)(ii) The vehicle is backed up only when an observer signals that it is safe to do so” (Part 1926.601[b][4]). Also, for construction moving machines, OSHA standard number 1926.602 states, “No employer shall permit earthmoving or compacting equipment which has an obstructed view to the rear to be used in reverse gear unless the equipment has in operation a reverse signal alarm distinguishable from the surrounding noise level or an employee signals that it is safe to do so” (Part 1926.602[a][9]).

Scientific Research on the use of Backup Alarms and Hearing Protection Devices in Construction Industry

Scientific, human factors research conducted at Virginia Tech consisted of two experiments to: 1) test how listeners with normal hearing localize backup alarm signals in the horizontal dimension, and 2) to test how they detect backup alarm signals in an open field and quantifying the distance at auditory detection. Their localization performance was assessed while they were listening to standard (tonal and narrowband) and spectrally-modified (tonal and broadband) backup alarm signals, while their detection performance was assessed while they were listening to standard (tonal and narrowband) and broadband (pulsed white noise - Brigade™) backup alarm signals. During this assessment, listeners were unoccluded or fitted with hearing protection devices (HPDs) that represented the most recent technology in augmented passive and active HPDs, as well as conventional passive HPDs, available in the market circa mid-2010.
The resultant data indicated the following:

1. Adding low and high frequency components to the standard backup alarm signal will improve listeners’ perception of its direction, i.e., localization. This is because low frequencies provoke an Interaural Time Difference (ITD) and high frequencies provoke an Interaural Level Difference (ILD), both of which are important to foster sound localization.

2. Exposure to high levels of background noise (90 dBA) significantly degrades localization performance as compared to exposure to low background noise levels (60 dBA).

3. The diotic design (one microphone feeding both earcups) for sound transmission earmuffs significantly disrupts listeners’ localization performance more than any other tested HPD and also increased the localization response time to the backup alarm over that achieved with the open ear condition, the E-A-R/3M HiFi™ earplug, and the E-A-R/3M Arc™ earplug.

4. There was no significant difference between any of the HPDs and the open ear listening condition in localization performance when listeners were exposed to 90 dBA, except for the diotic earmuff which stood alone as the worst.

5. The E-A-R/3M HiFi™ earplug, which has a uniform attenuation across its attenuation spectrum, provided better localization performance at high levels of background noise (i.e., 90 dBA) than the common foam earplug. In addition, listeners were more confident in their localization decisions when they were fitted with the E-A-R/3M HiFi™ earplug as compared to most of the tested HPDs.

6. Listeners’ localization performance when they were fitted with the passive earmuff was identical to their performance when they were fitted with the dichotic sound transmission earmuff; thus there was no directional benefit of the electronic muff.

7. HPDs with high attenuation values significantly reduce the distance at detection to backup alarms as compared to HPDs with moderate attenuation values (e.g., E-A-R/3M HiFi™ earplug).

8. Listeners were able to detect the standard (tonal and narrowband) backup alarm signal at longer distances as compared to the broadband (pulsed white noise - Brigade™) backup alarm signal.

**Recommendations for Application of the Virginia Tech Research Results**
While the results of the two research experiments are limited to the HPDs, noise levels, and backup alarms under test, several important conclusions can be drawn. If localizing backing vehicles in construction sites is crucial for on-foot workers safety, then construction safety professionals should:

1. Install on construction vehicles a tonal backup alarm which incorporates low and high frequency components that are important to foster sound localization, but not extend the frequency content to the point of the alarm becoming a white noise.
2. Reduce background noise levels to the extent possible.
3. Avoid providing diotic sound transmission earmuffs where construction workers must orient to the alarm.
4. Provide workers with uniform-attenuation hearing protectors (e.g., the E-A-R/3M HiFi™ earplug) when construction workers are exposed to noise levels that are appropriate to the moderate attenuation afforded by them.
5. Be aware that using passive earmuffs will likely provide the same localization performance as when using dichotic sound transmission earmuffs. This result, at least for normal-hearing workers, has financial implications since dichotic muffs are relatively expensive. However, it must be realized that due to design variations, other electronic HPDs may perform differently.

Also, to allow construction workers to detect backup alarm signals at longer distances, and thus provide them with ample time to react to backing vehicles, construction safety professionals should:

1. Provide workers with hearing protectors that have moderate attenuation (e.g., the E-A-R/3M HiFi™ earplug), if noise exposures are sufficiently reduced by them.
2. Install tonal backup alarms on the construction vehicles instead of a broadband (pulsed white noise) backup alarm.

Further details on the previous research results can be found in: