INFLUENCE OF EAR CANAL OCCLUSION AND AIR-CONDUCTION FEEDBACK ON SPEECH PRODUCTION IN NOISE

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University of Pittsburgh, 2013

Millions of workers are exposed to high noise levels on a daily basis. The primary concern for these individuals is the prevention of noise-induced hearing loss, which is typically accomplished by wearing of some type of personal hearing protector. However, many workers complain they cannot adequately hear their co-workers when hearing protectors are worn. There are many aspects related to fully understanding verbal communication between noise-exposed workers that are wearing hearing protection. One topic that has received limited attention is the overall voice level a person uses to communicate in a noisy environment. Quantifying this component provides a starting point for understanding how communication may be improved in such situations.

While blocking out external sounds, hearing protectors also induce changes in the wearer's self-perception of his/her own voice, which is known as the occlusion effect. The occlusion effect and attenuation provided by hearing protectors generally produce opposite effects on that individual's vocal output. A controlled laboratory study was devised to systematically examine the effect on a talker's voice level caused by wearing a hearing protector and while being subjected to high noise levels. To test whether differences between occluded and unoccluded vocal characteristics are due solely to the occlusion effect, speech produced while subjects' ear canals were occluded was measured without the subject effectively receiving any attenuation from the hearing protectors. To test whether vocal output differences are due to

the reduction in the talker's self-perceived voice level, the amount of occlusion was held constant while varying the effective hearing protector attenuation.

Results show the occlusion effect, hearing protector attenuation, and ambient noise level all to have an effect on the talker's voice output level, and all three must be known to fully understand and/or predict the effect in a particular situation. The results of this study may be used to begin an effort to quantify metrics in addition to the basic noise reduction rating that may be used to evaluate a hearing protector's practical usability/wearability. By developing such performance metrics, workers will have information to make informed decisions about which hearing protector they should use for their particular work environment.

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1.0 INTRODUCTION

The discrimination of different speech sounds (i.e., the ability to understand what someone is saying) is one of the most important functions of the human auditory system. As everyone has experienced numerous times in their everyday lives, it is easier to hear and understand what is being said in some situations, while listening is much harder in other circumstances. For the approximately 22 million Americans who are occupationally exposed to hazardous noise (Tak, Davis, & Calvert, 2009), speech interference is a particularly bothersome effect of a noisy work environment.

Current occupational safety and health standards/regulations are primarily concerned with protecting workers from the harmful effects of high noise levels, and do not specifically mention communication issues (OSHA, 1983). Much of the scientific research involving speech intelligibility focuses on the acoustical environment, the hearing ability of the listener, and to a lesser extent, whether hearing protectors were worn. Some research also has been conducted to investigate the influence of background noise or hearing protection on the vocal output of an individual. Although the results are inconclusive, these studies have shown that occluding a person's ears can have an effect on how that person produces and perceives his/her own speech. Therefore, understanding speech communication issues that industrial workers face requires investigation of the effects of background noise and hearing protectors for both the talker as well as the listener.

Many workers require good speech intelligibility for the safe performance of their jobs. Identification or development of suitable strategies for communicating under difficult listening conditions would be useful for occupationally noise-exposed individuals. It would be helpful to accurately assess a worker's communication ability with an appropriate and easily administered speech intelligibility test. A review of the literature contained herein reveals that none of the existing commercially available tests were recorded while the talker was exposed to noise and was wearing hearing protectors. Test materials recorded under these conditions are needed to develop a valid speech intelligibility test for use with noise-exposed workers. However, not all of the underlying factors that would go into constructing such a test are completely understood. For example, the interaction between the occlusion effect, the amount of attenuation provided by a hearing protector, and their effects on speech produced in a noisy workplace has not been adequately explained in the literature. Herein is outlined a laboratory-based experiment in which these issues are investigated in order to provide a foundation for future research in this area. The intent was to develop a better understanding of how workers communicate while wearing hearing protection in a noise-hazardous environment, with the ultimate goal of optimizing workers' communication abilities while preserving their hearing ability.

2.0 BACKGROUND

Studying speech intelligibility under hazardous noise conditions includes elements from several related disciplines such as acoustics, audiology, and speech science. Beginning with the basic acoustical characteristics of speech production, several variables must be identified and understood. When high noise levels are present, these variables include changes in vocal output, the influence of hearing protective devices, and inter-relationships between the different variables. Identifying the specific tests/techniques appropriate for investigating these factors becomes an important issue.

2.1 SPEECH ACOUSTICS

2.1.1 Basics of speech production

Speech sounds are perhaps the most complex sounds an individual encounters on a daily basis, due to their rapidly changing acoustical characteristics. The speech-generating mechanism must therefore be a complex system capable of many modes of operation. The source-filter theory of speech production describes the basic mechanisms of speech production and examines articulatory-acoustic relationships (Stevens & House, 1961; Stevens, 1989). This theory analyzes speech outputs as a linear and time-invariant system of an acoustical energy source as modified by the response of a filter. The larynx is the primary source and the pharynx, mouth, and nose – together comprising the vocal tract – acts as the filter. Over the past 50 years, the source-filter theory has been thoroughly described in numerous texts (e.g., Fry, 1979; Picket, 1980; Kent, 1997; Kent & Read, 2002).

As air is exhaled from the lungs, it passes through the vocal folds, which can be thought of as an adjustable barrier across the air passage. A "voiced" sound is generated as the vocal folds vibrate in an essentially periodic manner. These sounds have a fundamental frequency (F_0) equal to the repetition rate of vocal fold vibration. They include all vowels, the nasal consonants /m n ng/, the liquid consonants /r l/, and glide consonants /w j/. Other speech sounds (e.g., /h f s p k t/) are produced when the vocal folds are open and not vibrating, or when the glottis is only momentarily blocked. In these cases, the sound source is aperiodic turbulence occurring either at the glottis or higher up in the vocal tract. A few speech sounds (e.g., /v z/) are generated by both a voiced source and a turbulent noise source being activated simultaneously.

After the source has been activated, the remaining length of the vocal tract alters the acoustic signal to form a speech sound. Similar to any other acoustic filter, the size, shape, and surface lining of the vocal tract dictate its acoustical properties. Although a complex acoustical system, in acoustic terms the vocal tract may be treated for simplicity as a lumped-parameter circuit. As such, it may be thought of as a resonator, meaning that it naturally enhances certain frequencies (or reduces them through anti-resonances). Resonant frequencies of the vocal tract are called formants, and these resonance patterns form the basis of most speech sounds. Continually adjusting the size and shape of the vocal tract filter system enables the different speech sounds to be produced. A listener learns to recognize the different speech sounds by distinguishing among the different patterns of formant frequencies and other sounds present in a speech sample. Diehl (2008) provides a review of the source–filter theory of speech production while addressing how acoustic and auditory properties of commonly occurring speech sounds ensure that speech is intelligible.

2.1.2 Long-term average speech spectrum

When analyzing speech, it is necessary to understand how individual sounds combine to form an overall acoustic spectrum. In this kind of analysis, a long sequence of connected speech (i.e., long enough for every sound to occur many times) is analyzed. The intensity level at each frequency is measured and summed to produce what is known as the long-term average speech spectrum (LTASS). Normally, the LTASS is plotted on a graph as decibel level (on the vertical axis) versus frequency (on the horizontal axis). The resulting curve shows the range of frequencies contained in the speech signal, and illustrates where the energy content is the greatest. Knowing the "normal" LTASS is essential to provide a basis for comparison when speech acoustics are applied to analyze different communication problems/situations.

Some of the earliest measurements of the LTASS were conducted at the Bell Telephone Laboratories. Dunn and White (1940) asked eleven subjects to read aloud continuously at a normal voice level while filters were used to analyze the speech spectrum. These data were used to help solve telephone transmission and/or speech reproduction problems. Due to equipment limitations, only one frequency band could be measured at a time, and the subject had to repeat the same passage several times in order to obtain a measurement for each frequency band of interest. Nevertheless, the overall level and distribution of speech energy was determined. In a later paper, French and Steinberg (1947) summarized the factors of speech (e.g., spectrum, levels) which had been identified by the end of World War II.

Several studies involving measurement of the LTASS have been performed since the pioneering work conducted before 1950. Many of these studies were conducted to provide hearing aid fitting information (Olsen, Hawkins, & Van Tasell, 1987; Cox & Moore, 1988; Cornelisse, Gagne, & Seewald, 1991; Stelmachowicz, Mace, Kopun, & Carney, 1993; Pittman, Stelmachowicz, Lewis, & Hoover, 2003; Holube, Fredelake, Vlaming, & Kollmeier, 2010). Others were intended for the assessment of voice pathologies or other vocal characteristics (Wendler, Doherty, & Hollien, 1980; Kitzing, 1986; Lofqvist & Mandersson, 1987; Mendoza, Valencia, Munoz, & Trujillo, 1996; Linville, 2002).

A comprehensive study involving measurement of the LTASS was conducted by a large group of researchers from several different countries (Byrne et al., 1994). The intent of this study was to develop a standard LTASS that would represent a wide range of languages, or to identify any significant differences that exist among languages. Toward this goal, the LTASS and dynamic range of speech were measured for 12 languages. The overall finding was that the LTASS was essentially similar across all languages included in the study. Most language/dialect differences yielded less than 3 dB differences in spectral levels, and the authors did not find any obvious explanations even for the few statistically significant differences. Males had higher intensities at 160 Hz and below, which is expected due to a lower fundamental frequency of the male voice. Males and female vocal levels were virtually identical from 250 Hz to 5000 Hz, and female voices contained more energy at 6300 Hz and higher. The authors concluded that a "universal LTASS" would be representative of most languages, due to the similarity found across all speech samples. More recently, Holube, Fredelake, Vlaming, and Kollmeier, (2010) published a report on the development of an International Speech Test Signal (ISTS) for analyzing how a hearing aid processes speech signals. The ISTS was developed using recordings of real speech in six different languages. The intent was to develop a test signal that contained all relevant characteristics of natural speech, but was predominantly unintelligible.

2.2 SPEECH PRODUCTION IN NOISE

2.2.1 The Lombard effect

First described by Etienne Lombard in 1911 (as cited in Lane and Tranel, 1971), the Lombard effect is usually described as the spontaneous tendency to increase one's vocal intensity when talking in the presence of strong background noise. The original use of "Lombard Masking" was to uncover phonation in patients with functional aphonia. It was observed that for some patients with weak voices, masking often seemed to "energize" the voice (i.e., masking was used to uncover a better, louder voice). The Lombard effect also has reportedly been used to assist in the treatment of stuttering (e.g., Howell, 1990), since some stutterers reduce the frequency of stuttering under noisy conditions. Additional research using the Lombard effect has involved voice disorders resulting from other conditions such as Parkinson's disease (e.g., Ho, Bradshaw, Inasek, & Alfredson, 1999) and spasmodic dysphonia (e.g., McColl & McCaffrey, 2006).

Audiologists typically learn about the Lombard effect when studying tests for patients with non-organic hearing loss (Newby, 1979). Theoretically, an individual should not change vocal intensity unless the background noise is well above his/her hearing threshold. Therefore, the Lombard test is performed by having the patient read a passage aloud while masking noise is played through headphones, and the clinician monitors the patient's voice level. The masking noise is gradually increased, and a corresponding increase in vocal level should only occur when the masking noise exceeds the patient's admitted hearing threshold level. Unfortunately, the Lombard test has limited diagnostic value because even if the Lombard effect is observed, this only proves that the person heard the masking noise -- it does not provide an estimate of the person's true hearing thresholds. Hanley and Harvey (1965) worked on a technique to objectively score the Lombard test; however, their method was never fully developed and it never gained widespread clinical acceptance.

Pick, Siegel, Fox, Garber, and Kearney (1989) investigated a person's ability to suppress the Lombard effect in a three-part experiment. First, they observed a stable and robust Lombard effect over repeated exposures to quiet and noise conditions, which suggested that the increased vocal level in noise is automatic and difficult to suppress. Next, they found that when given instructions to resist talking louder, experienced/sophisticated subjects were better able to maintain a constant vocal level than naïve subjects; however, none of the subjects were able to suppress the Lombard effect completely, even when instructions were combined with a visual feedback display. The final component of their experiment used a single-subject format involving more intensive training and instructions in the use of visual feedback. Visual feedback was successful in teaching the subjects to lower their vocal output, and the lower vocal intensities were still observed when the feedback was removed. However, the subjects essentially "overcompensated" and carried over the tendency to speak more softly in a quiet environment. Therefore, rather than learning to talk softly (i.e., suppress the Lombard effect) the subjects may have just shifted their overall vocal level downward in both noise and in quiet. Although these results generally suggest a non-voluntary origin, it is still not clear whether the Lombard effect is the result of an "automatic" regulating mechanism (i.e., the talker cannot simply ignore the background noise) or whether speakers learn to increase their vocal intensity to avoid a communication breakdown (i.e., the talker knows that he/she will be misunderstood if his/her voice is not raised). The Lombard effect varies with the social context and speaker task, which would indicate that regulation of speech amplitude is not just a simple auditory feedback mechanism (Amazi & Garber, 1982; Garnier, Henrich, & Dubois, 2010).

Winkworth and Davis (1997) studied the Lombard effect to examine whether respiratory patterns during speech changed according to the level of background noise. They used five healthy women subjects and measured respiratory function with two pairs of linearized magnetometers placed on the rib cage and abdomen. A multi-talker babble played through headphones was used as the background noise. Two speech tasks (a 30 second reading and a 2-3 minute spontaneous monologue) were recorded under three noise conditions (quiet, 55 dBA, and 70 dBA) for a total of six speech samples per subject. A robust Lombard effect was found for these subjects, while no consistent trend of lung volume change was observed with the linear increases in speech level. The authors concluded that since the subjects increased their speaking level without being specifically instructed to do so, the loudness changes were produced by individualized changes in breathing patterns for each subject.

Huber, Chandrasekaran, and Wolstencroft (2005) conducted a study to determine whether speaking louder resulted in different respiratory kinematic patterns while reciting a 6-syllable and a 12-syllable sentence. This investigation was prompted by the findings of Winkworth and Davis (1997) that showed that an individual's respiratory kinematics might change, based on the cue used to illicit the louder speech. The Huber et al. (2005) study investigated the differences if the subject was asked to speak louder or if he/she automatically spoke louder due to noise in the background. They found that asking subjects to target a specific sound level 10 dB above comfortable, asking them to speak twice as loud as is comfortable, and asking them to speak in

70 dBA multi-talker babble all resulted in the same sound pressure level output. The respiratory kinematic measurements revealed that different mechanisms were responsible in each condition. Subjects used a combination of increased recoil pressures and increased expiratory muscle tension when asked to speak in the background noise. A slower speech rate also was observed in this condition.

A follow-on study was reported by Huber (2007) where she used the same basic procedures as in Huber et al. (2005) using a connected speech task as opposed to the two sentences from the earlier study. A second purpose was to examine whether the type of speech task affected respiratory kinematics at a comfortable speaking level and in 70 dBA multi-talker babble. The same differences in respiratory strategies for the different test conditions (as seen in the previous study) were observed. Huber (2007) suggested that different cues to increase loudness – i.e., the intention/goal of the talker – play a role in the control of respiratory kinematic movements.

2.2.2 Other vocal characteristics

In addition to investigating overall sound pressure level changes caused by high ambient noise levels, other studies involving Lombard speech have examined vocal characteristics such as changes in fundamental frequency, spectrum content, and speaking rate. In general, a talker's fundamental frequency increases, the spectrum content shifts to higher frequencies, and the speaking rate decreases in the presence of background noise. An earlier study involving communication in noise found that a subject will perform such changes without having been trained to do so (Hanley & Steer, 1949).

Rivers and Rastatter (1985) examined how white noise and multi-talker babble (both presented at 90 dB SPL) influenced the fundamental frequency of children and adults. All subjects increased their mean fundamental frequency under both masking conditions. With a few exceptions, larger standard deviations were found when subjects spoke in the noise conditions as compared to speaking in quiet. A follow-on study (Loren, Colcord, & Rastatter, 1986) was conducted to further assess the effects of speaking against a background of white noise on the variability of an individual's fundamental frequency. Consistent with the earlier study, the mean fundamental frequency increased when subjects spoke while listening to the white noise.

Summers, Pisoni, Bernacki, Pedlow, and Stokes (1988) reported on a study that was intended to specify the gross acoustic-phonetic changes that take place when speech is produced in high levels of noise (e.g., in an aircraft cockpit). In the first part of this study, two male subjects read aloud words from the Air Force speech recognition vocabulary under four background noise conditions (quiet, 80 dB, 90 dB, and 100 dB of broadband masking noise). The subjects were instructed to read each word as clearly as possible while the experimenter listened and recorded their speech. Reliable and consistent differences were found between the quiet and noise conditions. As expected, results were consistent with earlier studies reporting changes in prosodic features (e.g., increases in word duration, vocal intensity, and high frequency content). Additionally, the authors reported changes in the pattern of vowel formant frequencies.

An experiment was performed a few years later (Tartter, Gomes, & Litwin, 1993) to replicate and expand upon the 1988 Air Force study. As found in earlier studies, their frequency analysis indicated a flatter tilt in speech spectrums obtained for subjects talking in the high noise condition, which means that there was an increase in the amplitude of high frequencies. This study also replicated the effect of talking in noise on speech duration and amplitude, both of which increased with higher background noise levels. Significant changes in F1 and F2 were observed for some words but not others.

Bond, Moore, and Gable (1989) studied several prosodic and acoustic properties of speech in four subjects listening to 95 dB pink noise under headphones. In addition to increased amplitude (the Lombard effect), they found increases in fundamental frequency, vowel duration, and a shift in the F1-F2 vowel quadrilateral. The differences in vowel production were attributed to adjustments in lower jaw position and mouth opening when speaking in the presence of noise.

Another study was conducted to determine the speech rate, vocal pitch, overall sound pressure level, and spectral characteristics of connected Lombard speech (Letowski, Frank, & Caravella, 1993). These researchers used multi-talker babble, traffic noise, and a wideband (flat spectrum) noise presented at 70 dB and 90 dB. They investigated the differences among talkers in the different noise conditions as compared to their speech produced in quiet. Consistent with other studies, they found an increase in overall sound pressure level and higher vocal pitch in Lombard speech as compared to speech produced in quiet. Unlike other studies, they did not find significant differences in overall voice level for the three noise types or decreased speech rate.

2.2.3 Summary

Table 1 summarizes the pertinent findings of the most significant studies reviewed in this section.

Table 1. Studies involving speech production in noise.

Study	Research Objective	Subjects	Indep. Variables	Dependent Variables	Relevant Findings
Lane & Tranel (1971)	Review article of previous research involving the role of hearing in speech production, specifically the Lombard Effect				Talkers spontaneously raise vocal intensity when talking in the presence of background noise; authors suggested this is learned in an attempt for the talker to be heard over the noise
Pick et al. (1989)	Test robustness of the Lombard Effect when subjects are given instructions to suppress it	Experienced and naïve listeners (24 - all normal-hearing)	Quiet vs. 90 dB SPL background noise; visual feedback	Vocal intensity levels	The Lombard Effect is very stable; subjects could inhibit the Lombard effect in trained/sophisticated subjects; findings suggest that it is an automatic normalization response
Winkworth & Davis (1997)	Examine changes in respiratory patterns during speech production	5 normal-hearing females	Quiet, 55 dB multi-talker noise, and 70 dB multi-talker noise	Speech intensity, lung volumes, speech breath durations, rib cage and abdominal changes	No consistent trend of lung volume change was observed with the Lombard effect; loudness changes were produced by individualized changes in breathing patterns for each subject
Huber et al. (2005) and Huber (2007)	Investigate how cues affect respiratory function in normal speakers, in order to identify the best cues for clinical treatment (i.e., to increase loudness) in patients with reduced vocal outputs	30 normal-hearing adults (15 male and 15 female)	Comfortable reading level; 10 dB above comfortable level; twice the comfortable level; 70 dB multi-talker noise	Speech SPLs; maximal capacity of lungs, rib cage, and abdomen	Respiratory mechanisms used to increase loudness differed depending how the increase in loudness was elicited; different cues resulted in different internal targets; neural control of the respiratory system for speech is affected by changes to the talker's internal loudness target; the talker's intention or goals play a role in the control of respiratory function during speech
Hanley & Steer (1949)	Determine the need for training individuals who will be using radio-telephone communication systems	48 male college students	Four levels of airplane-type noise	Words spoken per minute, mean syllable duration, speech intensity level	Untrained subjects speaking in noise naturally react in a desirable manner – they reduce speaking rate, prolong syllables, and speak louder

Table 1 (continued).

Study	Research Objective	Subjects	Indep. Variables	Dependent Variables	Relevant Findings
Rivers & Rastatter (1985) and Loren, Colcord, & Rastatter, (1986)	Examine the manner in which various forms of auditory disruption (ambient noise) affect the hearing/speaking regulatory mechanism	10 normal-hearing adults (5 men and 5 women); 28 children aged 5-10 years	Quiet, 90 dB SPL white noise, 90 dB SPL multi-talker noise	Fundamental frequency (f0)	Fundamental frequency increased when subjects spoke in a background of noise; variability of f0 was not affected; the authors suggest that the auditory system serves as a servo-mechanical monitor in regulating f0 under certain listening conditions
Summers et al. (1988) and Tartter et al. (1993)	Examine the acoustic-phonetic changes in the speech produced by talkers in high ambient noise; improve signal processing algorithms for speech recognition in noise	2 adult males (1988); 2 adult females (1993)	Quiet, 80, 90 and 100 dB white noise Quiet, 35, 60 and 80 dB white noise	Speech SPLs, fundamental frequency, vowel formant frequencies, utterance duration	Increases in speech duration, intensity, and high frequency energy with greater noise levels; variable increase in fundamental frequency; no consistent changes in first or second formant frequencies across speakers or words
Bond et al. (1989)	Investigate changes in the prosodic and acoustic-phonetic features of talkers in 95 dB pink noise (w/ & w/o wearing an O_2 mask)	4 male college students, experienced as subjects	Mask/no mask conditions; quiet and 95 dB pink noise	Word durations, formant frequency, fundamental frequency, speech levels	This study replicated the findings of others: speaking in the presence of noise causes an increase in f0, amplitude, vowel duration, and shifts in the center frequencies of the first two formants of vowels
Letowski et al. (1993)	Measure several acoustical properties of Lombard speech; determine changes in speech rate, vocal pitch, overall SPL, and spectral characteristics of connected speech produced by subjects in quiet compared with the same speech produced in noise	10 normal-hearing adults (5 men and 5 women)	Quiet, multi-talker noise, traffic noise, and wideband noise at 70 and 90 dB SPL	Speech rate, vocal pitch, overall SPL, spectral content	Replication of other studies: Lombard speech is characterized by an increase in overall SPL and higher vocal pitch than speech produced in quiet; overall SPL of Lombard female and male speech are similar; smaller changes in vocal pitch are present for female compared with male Lombard speech; Note: contrary to some reports, did not observe systematic changes in speech rate with increased noise levels.

2.3 EFFECT OF "LOUD SPEECH" AND NOISE ON INTELLIGIBILITY

A few of the earliest studies found a linear relationship between speech presentation level and recognition performance. Hawkins and Stevens (1950) reported that speech intelligibility thresholds were raised by 10 dB by each 10 dB increase in noise level. However, most of the subsequent studies have found an inverse relation between presentation level and recognition performance. Pickett (1956) found that speech intelligibility scores dropped significantly when phonetically balanced test words were recorded with a strong vocal force. In this study, speech was elicited from subjects at eight levels ranging from very soft to loud shouting. Intelligibility dropped off significantly as the vocal effort increased from "very loud" (78 dB) to "maximum shout" (90 dB). Data for specific voice parameters were not collected, although shouting degraded the initial and final parts of a syllable rather than the middle section. When produced with a shouted voice, the intelligibility of vowels with higher first formant frequencies was less than for vowels with lower first formant frequencies (Pickett, 1956).

Studies have demonstrated that intelligibility suffers when speech is presented at higher-than-normal levels. Intelligibility also decreases when loud speech is produced in quiet conditions but is not as affected when spoken in background noise. French and Steinberg (1947) reported decreases in intelligibility when the presentation level was much higher than a normal vocal level, without any background noise. Dreher and O'Neill (1957) reported that a talker producing speech while listening to masking noise is more intelligible than when his speech is produced in quiet. Pollack and Pickett (1958) found decreases in intelligibility when speech was presented at very high levels (up to 130 dB) without background noise.

One of the findings reported by Summers et al. (1988) was that Lombard speech is more intelligible than "loud" speech produced in quiet. Perceptual analyses were conducted as a part of their study, and it was concluded that speech recognition was more complicated than simply adding background noise to an intelligibility task. Studebaker, Sherbecoe, McDaniel, and Gwaltney (1999) reported that intelligibility in noise decreased when the speech was presented at lower levels (69 dB SPL and above) than reported by earlier researchers, with the signal-to-noise ratio remaining constant. They also concluded that there is an interaction between speech and background noise levels, which was described as follows: When speech was presented at approximately conversational levels, an increase in noise level caused reduced intelligibility which could be predicted by the resulting reduction in audibility. At higher speech levels, however, intelligibility decreased more rapidly than would be expected. Experiments by Pittman and Wiley (2001) revealed findings consistent with earlier studies in this area. They conducted a two-part study to examine the recognition of speech produced in quiet and in noise. In the first part, acoustic analysis of speech found increases in vocal level, frequency content, and word duration when the talker heard 80 dB SPL wideband noise or multi-talker babble. Subsequently, higher speech recognition scores were obtained for the speech produced in noise.

Using the same digitized speech samples and masker spectrum from the Studebaker et al. (1999) study, Dubno, Horwitz, and Ahlstrom (2005) conducted a study to further explore speech recognition in higher-than-normal levels of speech-shaped noise. Word lists were presented to subjects at three levels for each of three signal-to-noise ratios (-2, +3, and +8 dB). The speech varied from moderate to high levels: 68, 75, and 82 dB for the -2 dB S/N ratio; 73, 80, and 87 for the +3 dB S/N ratio; and 78, 85, and 92 dB for the +8 dB S/N ratio. As previously reported, word recognition was found to decrease as the speech level increased, despite maintaining a constant signal-to-noise ratio. The authors attributed this finding to a non-linear growth in masking and a reduced effective signal-to-noise ratio with the higher masker levels.

Not all studies reported the same findings as discussed so far. While studying the Lombard effect as it relates to automatic speech recognition systems, Junqua (1993) reported that the type of masking noise, the test materials, and the talker's gender were found to influence speech intelligibility. Using single digits (i.e., the numbers 0 to 9) as the test stimuli, intelligibility scores were lower against a multi-talker babble, as compared to the scores when white noise was used as the masker. Conversely, intelligibility was higher for the multi-talker babble condition when the test stimuli were an easily confusable letter/number list (b, c, d, e, g, p, t, v, z, and the number 3), as compared to the white noise masking condition. He observed that a white noise spectrum affected consonant sounds more than multi-talker babble did, while the multi-talker babble affected the vowel sounds to a greater extent. Females were found to be more intelligible than males when evaluating speech production in noise, which was the opposite for speech produced in quiet. Junqua (1993) also concluded that the Lombard effect is highly variable among different talkers. The findings in this study differ from the previously discussed studies in that intelligibility decreased for speech produced in 85 dB SPL white noise as compared to the same speech produced in quiet.

A related concern for speech communication in high noise environments is the potential adverse effect on the talker's vocal mechanism. Pickett (1956) reported that the maximum shouting level was 100-105 dB SPL, while the loudest level that could be sustained without painful voice fatigue was 90 dB. Newer research found similar voice levels (Olsen, 1998; Cushing, Li, Cox, Worrall, & Jackson, 2011). Most individuals are unlikely to continue talking at such a high level for more than a brief period of time. Voice problems are common among teachers, singers, and other occupations that involve public speaking (e.g., Verdolini & Ramig, 2001), although little has been reported specifically on vocal pathology in noise-exposed workers. An example of research applicable to this issue involves a project supported by the Swedish Council for Working Life and Social Research that investigated health risks caused by overly loud phonation. Sodersten, Ternstrom, and Bohman (2005) used a method to prevent the competing noise from contaminating the recorded speech signal during speech-production-in-noise voice analysis to study voice production in four different types/levels of environmental noise. They found the same types of acoustic changes as reported previously, and also reported on a subjective perceptual analysis including vocal fry, strain, press, instability, and roughness. The same subjects participated in a companion experiment to develop an acoustic description of overloaded voice (Ternstrom, Bohman, & Sodersten, 2006). This study found that high frequency content will reach a maximum as the overall SPL of an individual's voice is increased. A later article on this subject (Aronsson, Bohman, Ternstrom,& Sodersten, 2007) verified that speaking in background noise may lead to voice disorders (e.g., vocal nodules). They also noted that mechanical stress on the vocal folds may occur when speaking in background noise levels that are several decibels less than those considered as hazardous to an individual's hearing.

More recently, a project conducted by the Technical University of Denmark and the Voice Research Group at the Department of Logopedics, Phoniatrics and Audiology at Lund University investigated how teachers use their voices in relation to the acoustic properties of the classroom and whether speakers take auditory cues into account to regulate their voice levels (Brunskog, Gade, Bellester, & Calbo, 2009; Pelegrin-Garcia, 2011; Pelegrin-Garcia, Fuentes-Mendizabal, Brunskog, & Jeong, 2011). Among other findings, this line of research developed new acoustic measures (i.e., voice support and room gain) that are well correlated with the changes in voice level observed in rooms with differing acoustical attributes. Their findings also support the idea that a room's acoustics has an effect on voice production, most notably that high background noise levels induce an increase in vocal effort.

Table 2 summarizes the pertinent findings of the most significant journal articles regarding the effect of loud speech and noise on speech intelligibility.

Table 2. Intelligibility studies involving loud speech and noise.

Study	Research Objective	Subjects	Indep. Variables	Dependent Variables	Relevant Findings
Hawkins & Stevens (1950)	Determine the masking effect of white noise on speech	4 listeners	Continuous discourse in quiet and sensation levels of white noise from 10-90 dB	Threshold of detectability; threshold of intelligibility	At higher noise levels, the thresholds for speech were raised by approx. 10 dB for each 10 dB increment in noise level
Pickett (1956)	Assess the effects of extremely high vocal effort on speech intelligibility	5 male talkers; same 5 subjects plus one additional served as listeners	Recordings of mono-syllable words (weak to strong vocal effort); Flat spectrum 70 dB noise at -6, 0, and +6 dB S/N	Correct/incorrect responses; error analysis (beginning, middle, or end of word)	Severe deterioration of intelligibility with extremely strong vocal force
French & Steinberg (1947)	Review the earlier research on speech and hearing; develop relationships for quantitatively expressing the intelligibility of speech sounds (i.e., calculating the Articulation Index)				Speech intelligibility decreases when the presentation level is much higher than a normal vocal level (summary of results from prior studies)
Dreher & O'Neill (1957)	Investigate the intelligibility of speech produced in noise, with the intent that any resulting changes that increase intelligibility might be exploited for voice communication applications	Talkers: 3 male and 12 female college students; Listeners: 204 college students	Spondee words and sentences recorded in quiet, 70, 80, 90, and 100 dB white noise	Intelligibility scores	There is a measurable and important increase in the intelligibility of both words and sentences produced by speakers listening to broadband random noise through a headset
Pollack & Pickett (1958)	Examine the deterioration of word intelligibility at high sound levels, to be used in a computational procedure for predicting speech intelligibility	4 talkers; 6 listeners	PAL PB words in 85-130 dB white noise; -5 to +55 dB S/N ratios	Percentage of words correctly identified	With a constant signal-to-noise ratio, monosyllabic word intelligibility decreases as the overall sound level is increased (due to overloading of the auditory system)

Table 2 (continued).

Study	Research Objective	Subjects	Indep. Variables	Dependent Variables	Relevant Findings
Summers et al. (1988)	Obtain quantitative measures of speech produced in quiet and in noise; verify earlier finding that speech produced in noise was more intelligible than speech produced in quiet when the two conditions were presented at equivalent signal-to-noise ratios	41 normal-hearing college students	Closed-set (15 digits & words) recorded in 90 and 100 dB white noise, presented at -5, -10, and -15 dB S/N ratios	Percentage of correct responses	Replicated the findings of Dreher & O'Neill (1957); subjects were more accurate at identifying utterances originally produced in noise than those produced in quiet
Stude-baker et al. (1999)	Determine how listening level and signal-to-noise ratio influence speech recognition by normal-hearing and hearing-impaired subjects at higher-than-normal speech and noise levels	72 normal-hearing young adults; 32 hearing-impaired adults under age 70; 12 hearing-impaired adults age ≥70 years	NU-6 words presented in quiet and speech-shaped noise (8 speech long-term RMS levels from 64-99 dB SPL and 10 S/N ratios from -4 to +28 dB)	Word recognition scores	Speech intelligibility in noise decreases when speech levels exceed 69 dB SPL and the signal-to-noise ratio remains constant; the effects of speech and noise level are synergistic, i.e., the negative effects of added noise level are greater when the speech level is high, and vice versa
Pittman & Wiley (2001)	Determine if the type of noise significantly influenced production of speech samples, and to determine the influence of two different listening conditions on speech recognition scores	27 normal-hearing women and 3 men between the ages of 18 and 30	50 low-predictability sentences from the SPIN Test recorded in quiet, and wide-band noise and multi-talker noise at 80 dB SPL, presented at -10, -5, and 0 dB S/N ratios	Target word recognition (percent correct)	Results were consistent with Summers et al. (1988); speech recognition tasks used clinically are of limited value for predicting communication difficulties in everyday situations that involve noise or competing speech because these tasks use speech samples recorded in quiet rather than in background noise

Table 2 (continued).

Study	Research Objective	Subjects	Indep. Variables	Dependent Variables	Relevant Findings
Dubno et al. (2005)	Further explore speech recognition in noise at higher-than-normal levels	9 normal-hearing adults, age 21 to 28 years	NU#6 words presented at three S/N ratios: +8, +3, and -2 dB, and three speech-shaped masker levels 70, 77, and 84 dB SPL	Word recognition scores as a function of speech-shaped masker level and S/N ratio	Word recognition in a speech-shaped masker declined significantly with increases in speech level when signal-to-noise ratio was held constant
Junqua (1993)	Summarize important characteristics of the Lombard reflex; review experimental results showing how the Lombard reflex varies with the speaker gender, the language, and the type of noise	9 French listeners, 10 English listeners, 10 non-trained American listeners, and 4 trained American listeners	Class of the listeners (French, English, American); type of words; size of the vocabulary; type of noise; gender of the speakers; speech quality evaluation measure	Percentage of correct responses	Results were inconsistent with most other studies, e.g., Dreher & O'Neill (1957), Summers et al. (1988), and Pittman & Wiley (2001); Junqua found significant decreases in the perception of digits and monosyllabic and bisyllabic words produced in noise

2.4 MEASUREMENT OF SPEECH INTELLIGIBILITY

2.4.1 Word tests

As an extension of the previous section, the type of test is another potentially important factor to consider when evaluating/conducting speech intelligibility studies. Speech intelligibility can be measured using various methodologies. Test protocols may contain varying types, numbers, and levels of independent variables including hearing status of the subjects, signal presentation level, speech-to-noise ratio, test methods (linguistic unit, cultural sophistication of listeners, response set, and/or psychophysical procedure), background noise masker, reverberation time, and whether hearing protection is being worn. Although numerous tests have been developed over the years, only the most commonly used tests are included in this review, and the (generally) commercially available tests are summarized in Table 3 at the end of this section.

The earliest tests were typically called articulation tests, and essentially described the relationship between the percentage of speech units correctly understood and the presentation level. This work was initiated by the need to develop specifications for speech transmission systems such as the telephone, interphones, and two-way radios. Working at the Bell Telephone Laboratories, Fletcher and Steinberg (1929, 1930) first summarized the development of lists of consonant-vowel-consonant (CVC) nonsense words and lists of discrete sentences. They noted that syllable discrimination scores compared well with sentence intelligibility scores, although when syllable discrimination was low the score for discrete sentences would be higher.

Egan (1948) reported on the development of speech test materials at the Harvard Psycho-Acoustic Laboratories (PAL) during World War II. Syllable lists consisting of VC, CV, and CVC words were created by pairing of consonants and vowels, with care taken to remove syllables that sounded like undesirable words and those that were difficult to pronounce. After much revision, 20 lists of 50 phonetically balanced monosyllabic words (PAL PB-50) were created. These lists were used to test for speech intelligibility and syllable recognition over various communication systems. The first American Standard Method for Measurement of Monosyllabic Word Intelligibility (American Standards Association, S3.2-1960) contained the PAL PB-50 word lists as test materials. After World War II, these lists would be used to evaluate the speech understanding ability of hearing-impaired soldiers and veterans.

Problems with the PB-50 word lists were identified as they were used clinically. Hirsh et al. (1952) attempted to improve on these clinical deficiencies, particularly to develop lists with more familiar words and produce suitably standardized recordings. A total of 200 words (four lists of 50 each) were used – 120 words from the original PB-50 lists plus an additional 80 words. Construction of the word lists was constrained by ensuring only monosyllabic words were used, no words were repeated in different lists, the words must be commonly used to minimize the effects of educational background of test subjects, and the phonetic composition of each list must correspond with the English language as closely as possible. This work was performed at the Central Institute for the Deaf, and the refinement of the PB-50 word lists became known as the CID Auditory Test W-22.

In an effort to eliminate the need for word familiarity and to reduce the influence of linguistic factors, Fairbanks (1958) and his colleagues developed the closed-set Rhyme Test. Testing in this manner evaluates phonemic differentiation rather than word recognition. Fifty sets of five monosyllabic rhyming words each were compiled. Within each set, the five words differed in initial consonant phoneme and spelling. Subjects were given a response sheet with 50 word "stems" (i.e., the rhyming portion), and the task was to enter the first letter to complete the spelling of the word that was heard. For example, for the "__ot" word stem, the listener might expect to hear hot, got, not, pot, or lot. The concepts of phonetic balancing and use of common words were carried over from the PB-50 and CID W-22 word lists.

Lehiste and Peterson (1959) developed 10 new lists of 50 monosyllabic words, which were referred to as consonant-nucleus-consonant (CNC) words since the middle vowel sound was called the "syllable nucleus." Instead of using the term phonetically balanced, they introduced "perceptual phonetics" or "phonemics," and asserted that the word lists should be described as being phonemically balanced. This is based on the concept that individual speech sounds will vary depending on the surrounding speech sounds. A few years later the CNC lists were revised to eliminate some rare and so-called literary words as well as two proper names that were in the original lists (Peterson & Lehiste, 1962).

Tillman and Carhart (1966) developed a new test using consonant-nucleus-consonant (CNC) monosyllabic words from Peterson and Lehiste (1962). This new test was called the Northwestern University (NU) Auditory Test No.6, which was an expansion of their earlier NU Test No.4. The NU-4 list was deemed to be too restricted since it only had 100 words, so the NU-6 test was constructed with 200 words divided into four phonemically equivalent 50-word lists. Since their development, the NU-6 and CID W-22 word lists have been routinely used in clinical audiologic testing. Audiologists commonly use only half lists (i.e., 25 words) to cut down the administration time. However, reducing the number of test items increases the variability and decreases test/re-test reliability (Thornton & Raffin, 1978; Walden, Schwartz, Williams, Holum-Hardegen, & Crowley, 1983; Cherry & Rubinstein, 2005).

House, Williams, Hecker, and Kryter, (1965) were interested in using tests of speech intelligibility to evaluate voice-communication systems. These authors cite problems with earlier speech intelligibility and articulation tests, such as their time-consuming nature and the requirement for listeners to be thoroughly trained on the word lists. To avoid these issues, they developed a closed-response-set test that has become known as the Modified Rhyme Test (MRT). The test format is similar to the Fairbanks (1958) Rhyme Test; however, word familiarity and phonetic balancing were not included in the MRT. Listeners are given an answer sheet that contains a set of six possible word alternatives for each test item. When taking the test, the listener indicates which one of the six choices was heard. Kreul et al. (1968) revised the MRT specifically for conducting speech discrimination testing in audiology clinics. Some words were replaced to eliminate potentially objectionable words and to reduce the number of times a particular word appeared among the response options. The revised recordings included a background noise so patients could be rank-ordered by their ability to discriminate speech under "everyday listening conditions." A relatively recent adaptation of the MRT was the addition of response time measures and using a word-monitoring paradigm rather than the original closed-set identification task (Mackersie, Neuman, & Levitt, 1999a, 1999b).

Another variation of a rhyming test called the Diagnostic Rhyme Test (DRT) was developed by Voiers (1977, 1983). The DRT is similar to the MRT in that it employs a closed response set of rhyming words, although the DRT uses a two-alternative forced-choice paradigm whereas the MRT provides six alternatives from which to choose. The DRT provides an analysis of the features of speech by providing possible response words that differ only by one distinctive feature. For example, /d/ differs from /t/ only by voicing, so the words dense and tense are paired as minimally contrasting response options for one test item. Test scores can therefore be analyzed separately for listeners' performance (understanding) for each feature of interest.

In 1989, the American Standard Method for Measurement of Monosyllabic Word Intelligibility (American Standards Association, S3.2-1960) was revised and renamed as the American National Standard Method for Measuring the Intelligibility of Speech Over Communication Systems (ANSI S3.2-1989). This Standard (which was revised in 2009) retained the original 1,000 PB-50 words (Egan, 1948) and added the Modified Rhyme Test (House et al., 1965) and the Diagnostic Rhyme Test (Voiers, 1977). The MRT in ANSI S3.2 has become the de facto standard test for much research-based (not clinical) speech intelligibility testing, since it is required in many military research and testing applications.

Although no new tests have been added to ANSI S3.2 since 1989, other word recognition tests have been developed in the past 24 years. In the early 1990s, the US Army used words from Form C of the NU-6 test to develop the Speech Recognition in Noise Test (SPRINT; described in Army Regulation 40-501, December 14, 2007). This test is administered to soldiers with a significant hearing loss in order to provide a recommendation to Military Medical Retention Boards regarding fitness for duty, assignment limitations, or discharge from the service. The SPRINT words are pre-recorded in a background of multi-talker babble at a 9 dB signal-to-noise ratio. Normal-hearing soldiers identify 95-100% of the words, whereas the performance of soldiers with hearing loss was found to vary considerably. Also using words from the NU-6 lists, Wilson (2003) developed the Words-in-Noise (WIN) test as a word-recognition task in multi-talker babble. Intended for clinical use, the test presents words at seven signal-to-noise ratios from 0 to 24 dB in 4-dB steps. Listener performance may be quantified by a percent correct score at each signal-to-noise ratio, the overall percent correct, and the 50% correct point on the signal-to-noise function. The 90th percentile (upper boundary of normal performance) for normal-hearing listeners was defined as a 6 dB signal-to-noise ratio (Wilson & McArdle, 2007).

Within the past decade or so, software-based word recognition tests such as the Computer-Assisted Speech Perception Assessment (CASPA) Test have been developed and evaluated (Mackersie, Boothroyd, & Minniear, 2001). The CASPA allows multi-level testing in quiet and noise, and was originally designed to assess hearing aid outcome. Separate scoring by words, phonemes, consonants, and vowels is provided. Phoneme scoring is desirable since it effectively increases the number of test items, whereas a full-word test with the same number of stimuli would require more time to administer. Computer-assisted tests such as the CASPA are intended to facilitate easy scoring by individual phonemes.

One of the newest word tests designed for assessing speech intelligibility in noise is the Callsign Acquisition Test (CAT; Blue, Ntuen, & Letowski, 2004; Rao & Letowski, 2006). This test was developed at the Army Research Laboratory specifically for evaluating the capabilities of various military communication systems in adverse listening environments. The CAT uses the military phonetic alphabet (i.e., a two-syllable alphabet code) and single-syllable numbers to form a three-syllable calling phrase (e.g., *alpha-one*, *bravo-two*, *delta-six*, etc.). Phonetic alphabets are used to reduce between-letter confusions and improve performance for interpersonal and radio communications.

2.4.2 Sentence tests

In addition to the numerous single-word tests that have been developed, sentence tests also have been devised. Intuitively, using sentences as test materials makes sense since listening to connected speech is a more realistic situation. Harris, Haines, Kelsey, and Clack (1961) published an article that investigated the dependence of intelligibility on some electro-acoustic characteristics of hearing aids. To conduct their experiments, they first had to decide the type of speech material that should be used. They began with 100 sentences (10 sets of 10) developed previously at the Central Institute for the Deaf, then revised the lists to make them all of equal length, and added some additional sentences using the 500 key words from the original CID lists. This new set became known as the revised CID (R-CID) sentence lists. Using low-pass filtering at 420 Hz, an experiment conducted by Giolas and Duffy (1973) did not find equivalent test scores for any of the original CID or R-CID sentence lists, and they concluded that the lists were not appropriate for clinical use.

The Speech Intelligibility in Noise (SPIN) Test (Kalikow, Stevens, & Elliott, 1977) was designed to examine linguistic-situational information in addition to the acoustic-phonetic components of speech. Test sentences are presented in 12-talker babble, and the last word of the sentence is the stimulus item, which is always a monosyllabic noun. Half of the sentences are termed high predictability where the key word is somewhat predictable from the context, and half are considered to be low predictability because the final word cannot be predicted from the context. This test was later evaluated using hearing-impaired subjects in an attempt at standardization and determination of list equivalence (Bilger, Neutzel, Rabinowitz, & Rzeckowski, 1984).

The Connected Speech Test (CST) is a test of everyday speech that was developed for use as a criterion measure when assessing hearing aid benefit (Cox, Alexander, & Gilmore, 1987). This test consists of passages of conversationally produced speech, where each passage contains 25 key words. The goal was to develop a test with high content validity, a large number of equivalent forms, and an acceptably small error of measurement. The inability of the SPIN test to provide these last two items was cited as incentive for developing a new test.

Nilsson, Soli, and Sullivan (1994) developed the Hearing in Noise Test (HINT) for measuring speech reception thresholds for sentences. Test materials were derived from the Bamford-Kowal-Bench (BKB) sentences which were designed for use with British children. The HINT consists of 24 equivalent 10-sentence lists that may be presented with speech-shaped background noise. Operating instructions indicate that a fixed-level protocol and percent-correct scoring may be used; however, this procedure may be subject to floor and ceiling effects on the psychometric function. A preferred alternative is to administer the HINT using a modified adaptive procedure and obtaining the speech reception threshold (i.e., 50% recognition point) instead of recording the absolute number of correctly repeated sentences. When speech-shaped noise is simultaneously played to the listener, test results are presented in terms of the signal-to-noise ratio required to obtain the speech reception threshold.

The QuickSIN™ is another sentence-in-noise test that is scored as the signal-to-noise ratio (in dB) required to achieve 50% recognition (Killion, Niquette, Gudmundsen, Revit, & Banjerjee, 2004). This test is a modification of the original Speech-In-Noise (SIN) test developed by Killion and Villchur (1993), which was later revised and renamed the RSIN test (Cox, Gray, & Alexander, 2001). Sentences for the SIN, RSIN, and QuickSIN were obtained from the Institute of Electrical and Electronics Engineers Recommended Practice for Speech

Quality Measurements (IEEE, 1969) which were derived from phonetically balanced sentences developed at Harvard University during World War II. The IEEE sentences are syntactically correct although they do not provide many contextual clues, so the listener is unlikely to correctly guess the entire sentence if only a few words are accurately heard. The QuickSIN contains six sentences with five key words per sentence pre-recorded in four-talker babble. The sentences are presented in 5-dB steps from a signal-to-noise ratio of 25 dB down to 0 dB, representing easy to difficult listening situations. In an effort to produce a test that was suitable for evaluating children and cochlear implant users, the developers of the QuickSIN used the same test paradigm to develop the Bamford-Kowal-Bench Speech-In-Noise (BKB-SIN) test using the BKB sentences as used in the HINT (Etymotic Research, 2005).

Table 3. Commonly used (or commercially available) speech intelligibility tests.

Name	Stimuli	Background Condition	Relevant Characteristics
CV, VC, and CVC	Syllable lists; nonsense words	Quiet	Earliest tests performed; used to assess intelligibility over the telephone (not commercially available)
PAL PB-50	Monosyllabic words	Quiet	Word lists were intended to satisfy these criteria: equal average difficulty; equal range of difficulty; equal phonetic composition; representative of English speech; words in common usage
CID W-22	Monosyllabic words	Quiet	Modification of PAL PB-50; easier and more homogeneous word lists due to improved phonetic balancing and test item familiarity; recorded on magnetic tape which permitted construction of several versions (word orders) where all occurrences of the same word were identical
NU-6	Monosyllabic words	Quiet	Based primarily on the CNC words from Lehiste & Peterson (1959) and Peterson & Lehiste (1962); commonly used in audiology clinics; commercially available recordings by both male and female talkers
MRT	Closed-set rhyme test	Quiet/noise	Six-alternative forced-choice scoring; less time-consuming to administer than monosyllabic word lists; subjects not required to be trained on test materials
DRT	Closed-set rhyme test	Quiet	Similar to MRT using a two-alternative forced choice paradigm; can obtain a feature analysis of errors
SPRINT	Monosyllabic words	Multi-talker babble	Used by the US Army to assess fitness-for-duty; words are pre-recorded in multi-talker babble at a 9 dB S/N ratio
WIN	Monosyllabic words	Multi-talker babble	Intended for clinical use; words presented in multi-talker babble at different S/N ratios
CASPA	CVC test stimuli	Quiet/noise	Designed to assess hearing aid outcome; computer-based; provides separate scores for words, phonemes, consonants, and vowels
CAT	3-syllable phrases	Pink noise; white noise; multi-talker babble	Developed by the US Army; based on military-specific language

Table 3 (continued).

Name	Stimuli	Background Condition	Relevant Characteristics
SPIN	Sentences	12-talker babble	Fifty sentences presented against a background of speech babble; listener repeats the final word in the sentence
CST	Speech passages (related sentences)	6-talker speech babble	Developed to improve upon the SPIN test; intended to be used to assess hearing aid benefit; test consists of 48 passages of connected speech – each passage contains 25 key words for scoring
HINT	Sentences	Speech-shaped noise	Commercially available; intended for adaptive measurement of speech reception thresholds in quiet or speech-shaped noise
QuickSIN	Sentences	4-talker speech babble	Commercially available; measures the signal-to-noise ratio a listener requires to understand 50% of key words in sentences against a background of speech babble; used to give hearing aid wearers realistic expectations for potential improvement in noisy listening conditions

2.5 EFFECTS OF HEARING PROTECTION ON INTELLIGIBILITY

2.5.1 Mechanisms of performance

Over 50 manufacturers have developed and sold at least 241 different hearing protection devices, many with quite high attenuation characteristics (NIOSH, 1994; updated information now maintained online at http://www.cdc.gov/niosh/topics/noise/hpcomp.html). A hearing protector that provides a high level of sound attenuation can greatly reduce the risk to the hearing mechanism, although it could increase the risk of accident or injury by creating an inability to hear important speech or warning signals. Hearing protectors that provide lesser amounts of attenuation might affect speech intelligibility differently, depending on the spectral and temporal characteristics of the noise as well as its overall level. Unfortunately, standard passive (non-electronic) and currently available electronically enhanced hearing protectors cannot selectively attenuate noise while leaving the speech unaffected. The effects of wearing hearing protectors extend both to the listener as well as the wearer of these devices.

Shaw (1982) and von Gierke (1954) provided detailed descriptions and acoustical models of passive hearing protector performance. These types of models may be presented as analogous electrical circuits or mechanical equivalents to aid in describing the acoustical concepts. Important parameters include the exposed surface area and mass of the protector, and enclosed volume under the earcup/earplug. For earmuffs, additional considerations include headband tension, earcup cushion/seal compliance, and acoustic absorption within the earcup. When numerical values are assigned to these variables, mathematical formulas may be used to calculate their typical transmission loss characteristics. Consistent with the acoustical properties of many materials, hearing protector attenuation is frequency dependent. Less attenuation is usually achieved at the lower frequencies as compared to higher frequencies. Generally, earplugs attenuate more than earmuffs at frequencies below 500 Hz, while both types of protectors perform much better above 2000 Hz. Research in this area is ongoing, and continues to provide additional insight into issues such as the effects of mass, clamping force, and earcup volume. Increasing these properties tends to increase earmuff attenuation (Zera & Mlynski, 2007; Pekkarinen, Starck, & Ylikoski, 1992; Williams, Seeto, & Dillon, 2012).

Conventional passive hearing protectors provide the same amount of attenuation, regardless of the incident sound level. However, specially designed passive protectors have been developed for specific noise environments. Although they are not necessary in most industrial noise situations, passive amplitude-sensitive devices are available that contain a non-linear component such as a very small orifice/duct opening (Allen & Berger, 1990). These non-linear protectors provide reduced attenuation at low sound levels (typically below 120 dB), with increasing protection at high levels, and are typically used for protection from gunshot or other impulsive noise sources.

The amount of protection afforded by a hearing protector depends on the way it is fitted and worn. Performance limitations may be imposed depending upon a hearing protector's construction and on the physiological and anatomical characteristics of the wearer. Sound energy may reach the inner ears of persons wearing protectors by four different pathways (von Gierke, 1954). Leaks around the protector are the primary concern, unless an air-tight seal is made with the ear canal walls (earplugs) or the side of the head (earmuffs). Second, the ambient sound pressure will cause the protector to vibrate, which in turn generates sound into the ear canal. Transmission of the sound directly through the protector itself may be another path, depending on the physical properties of the material. Finally, even with an optimally designed and properly fit hearing protector, sound may still pass through bone and tissue around the protector. Even if there are no acoustic leaks through or around a hearing protector, some noise will reach the inner ear by bone and tissue conduction if noise levels are sufficiently high (Zwislocki, 1957). The practical limits set by the bone- and tissue-conduction threshold vary significantly among individuals and among protector types, generally from about 40 to 60 dB (Berger, Kieper, & Gauger, 2003).

Hearing protector attenuation is determined either by conducting listening tests on human subjects or by direct acoustical measurement (Berger, 1986). Human subject testing is conducted by administering hearing tests to a panel of listeners with and without the protector in place. This test method is referred to as real-ear attenuation at threshold; the decibel difference between the open-ear threshold and the occluded-ear threshold indicates the amount of sound attenuation provided. Objective measurements are conducted using a microphone-in-real-ear technique, where the sound level in the ear canal or under the hearing protector is subtracted from the level in the open ear or outside the protector. Several attenuation rating methods have been developed (NIOSH, 1994), although the US Environmental Protection Agency requires the single-number noise reduction rating (NRR) to be shown on the label of each hearing protector sold in the United States (EPA, 1979). The NRR should be used cautiously because of its inherent lack of precision. A fundamental weakness of the NRR is that it can end up being controlled by just one or two of the nine one-third octave-band test signals used in its calculation. Generally, the controlling test signals are at or below 1000 Hz, and performance levels for other test signals may have little or no effect on the NRR. Another limitation of the NRR is that attenuation values obtained from laboratory testing tend to overestimate the amount of protection received by individuals during everyday use (Berger, Franks, & Lindgren, 1996). This is not surprising, considering that well-trained and highly motivated individuals are normally used in the laboratory as subjects, while the typical noise-exposed worker may not receive the necessary training or assistance with fitting his/her protectors. Despite the lack of real-world applicability, many hearing protector manufacturers have benefitted from relatively high laboratory-generated NRR values to sell more products than their competitors. The NRR, however, may be used as a general indication of how much noise reduction a particular hearing protector is capable of providing.

2.5.2 Listener effects

Kryter (1946) was one of the first researchers to investigate the effects of hearing protectors on speech intelligibility in noise. In his experiment, PAL phonetically balanced word lists were presented over a public address system while simulated submarine engine-room noise was played through loudspeakers in a reverberant test chamber. Normal-hearing subjects were tested both with and without earplugs in noise levels ranging from 65 to 115 dB. As the noise level increased, higher scores were obtained while wearing the earplugs as compared to the open-ear condition. Pollack (1957) also evaluated the effect of earplugs on speech intelligibility in normal-hearing listeners. He found little difference between the protected and unprotected speech intelligibility scores in broadband noise up to 100 dB. Better scores were obtained at even higher noise levels when the subjects wore earplugs. Howell and Martin (1975) reported on two experiments involving speech intelligibility, hearing protection, and noise. The results of the first experiment indicated that wearing hearing protection in noise levels above 85 dB will not cause degradation in intelligibility for the listener, and might even improve it. (The results of their second experiment will be discussed in the next section.)

A study of 537 Dutch industrial workers by Lindeman (1976) found that normal-hearing listeners (or those with only a slight high frequency hearing loss) demonstrated improved speech intelligibility while wearing earmuffs and listening to monosyllabic words presented at 90 dB with an 80 dB white noise background. Deterioration of intelligibility was found for subjects with a 30 dB or greater high frequency hearing loss. Rink (1979) also reported improvement in noise for normal-hearing listeners wearing hearing protection; however, his hearing-impaired subjects did not perform differently in noise whether or not hearing protection was worn. A possible explanation for this finding is that the hearing-impaired subjects did not have significant hearing losses; these subjects were described simply as having a minimum threshold of 30 dB for at least two audiometric test frequencies from 250 through 8000 Hz.

Chung and Gannon (1979) obtained results comparable to previous studies when testing normal-hearing and hearing-impaired subjects in pink noise at sensation levels of 40 and 65 dB. For the normal-hearing subjects, these levels would equate to approximately 65 and 90 dB SPL; the levels for the hearing-impaired subjects would have been higher, depending on their speech reception thresholds. Recognition of CID W-22 word lists was worse with earmuffs except for the normal-hearing listeners at high presentation levels. A distinct difference in responses between the protected and unprotected results was observed at a -5 dB signal-to-noise ratio, where most of the discrimination scores were below 50%. With the earmuffs on, most of the incorrect responses were actually “no response,” whereas most of the incorrect responses while not wearing the earmuffs were due to wrong answers. The authors suggested that the hearing protection attenuated the test stimuli below the level of audibility, and the speech became distorted by the loud noise if hearing protection was not worn.

A large study of speech intelligibility involving normal-hearing subjects, individuals with bilateral noise-induced high-frequency hearing loss, and individuals with bilateral flat hearing loss was conducted by Abel, Alberti, Haythornthwaite, and Riko (1982). Subjects listened to PAL PB-50 words presented at 80 or 90 dBA against an 85 dBA white or "crowd" noise while wearing five different types of hearing protectors. Results for normal-hearing listeners revealed essentially no effect, while subjects with both types of hearing losses performed significantly worse with the hearing protectors. No substantial differences between protector types were observed, although one of the two earmuffs used in this experiment caused somewhat lower scores than the rest of the devices. Other findings were that the crowd noise was a more effective masker than white noise, and individuals with flat hearing losses wearing hearing protection achieved the worst speech recognition scores.

Bauman and Marston (1986) conducted another study to investigate the effects of hearing protection on speech intelligibility, using a 0 dB signal-to-noise ratio in 85 dBA speech noise. Subjects with high frequency hearing loss had significantly worse scores than normal-hearing subjects. All subjects had poorer scores while wearing hearing protection, although the decrease was only a few percentage points for the normal-hearing group and the protected-unprotected difference was much more pronounced for the hearing-impaired subjects. Pekkarinen, Viljanen, Salmivalli, and Suonpaa (1990) also tested normal-hearing subjects at a 0 dB signal-to-noise ratio in 85 dBA noise (using broadband instead of speech noise). Their results were consistent with other studies that found significantly better intelligibility with earmuffs than without them. Similar results were found by Fernandes (2003), who conducted a study using Portuguese monosyllabic words in a pink noise background. In an evaluation of flat-attenuation earplugs, Plyler and Klumpp (2003) found improved HINT scores relative to the open-ear condition when the speech level was fixed at 90 dB SPL. The most recent study of this type did not find a difference between protected and unprotected HINT scores when a flat-attenuation earmuff was worn in a background of 85 dBA industrial noise (Dolan & O'Loughlin, 2005).

To summarize, several research studies have investigated the effect of hearing protectors on speech intelligibility over the past 67 years. Several types of background noises have been used in these studies including white noise, pink noise, and recordings of actual worksite noise. Some listening experiments were conducted using speech spectrum noise or multi-talker babble since they are the most efficient maskers of speech. Initial studies established that wearing hearing protectors in high ambient noise levels did not impair speech intelligibility. Actually, for some acoustic environments speech intelligibility can be improved by wearing hearing protection. Subsequent investigations confirmed these findings in normal hearing subjects, while discovering that hearing-impaired subjects performed worse on speech intelligibility tests while using hearing protection. Table 4 summarizes the studies reviewed in this section.

Table 4. Studies involving speech intelligibility while the subject is wearing hearing protection.

Study	Research Objective	Subjects	Indep. Variables	Dependent Variables	Relevant Findings
Kryter (1946)	Assess speech intelligibility in noise while wearing earplugs	8 college-age men	Speech over a PA system and direct person-to-person speech; noise at 65–115 dB, with and without earplugs	Percentage of PAL PB words correctly understood	Wearing earplugs does not impair, and in some cases improves the reception of speech in noise
Pollack (1957)	Examine the effect of hearing protection on speech intelligibility	(composition of the "testing crew" was not specified)	White noise (low-pass filtered at 1kHz) at 70–130 dB SPL, with and without earplugs	Percentage of words correctly understood	Hearing protectors provided large significant improvements in word intelligibility
Howell & Martin (1975)	Investigate the effect of wearing hearing protection on speech intelligibility	12 normal-hearing male university students	Ears open, earplugs, earmuffs; broadband noise at 65, 80, and 95 dB SPL	Intelligibility score (percent of monosyllabic words correct)	At low noise levels, listeners perform worse on intelligibility tests when hearing protectors are worn; when the noise is above 85 dB a slight improvement was seen
Lindeman (1976)	Study the effect of hearing protectors on normal-hearing and hearing-impaired workers	537 industrial workers with and without hearing loss	Ears open, earmuffs; quiet and 80 dB SPL white noise (word lists at +10 dB S/N ratio)	Percentage of monosyllabic words correct	Improvement in speech intelligibility was seen in normal or mildly hearing-impaired workers wearing earmuffs in noise; reduced intelligibility was seen in workers with more severe hearing losses
Rink (1979)	Evaluate the effect of hearing protectors on normal-hearing and hearing-impaired subjects	10 normal-hearing and 30 hearing-impaired adults	Quiet, 90 dBA broad-band noise; with/without earmuffs	Correct responses on the Modified Rhyme Test	Hearing protectors improve speech discrimination in noise for normal-hearing listeners; hearing protectors did not affect speech discrimination performance in noise for hearing-impaired listeners

Table 4 (continued).

Study	Research Objective	Subjects	Indep. Variables	Dependent Variables	Relevant Findings
Chung & Gannon (1979)	Repeat the earlier studies on speech intelligibility and hearing protectors with more conditions and a larger number of subjects	40 normal-hearing and 60 hearing-impaired males	Pink noise at approx. 80 dBA; speech at -5 and +10 dB S/N ratio, with and without earmuffs	Percent correct of CID W-22 word lists	General agreement was found with prior studies; subjects with normal hearing obtained higher word discrimination scores with hearing protection than without
Abel et al. (1982)	Investigate the effect of wearing hearing protection on speech intelligibility; define the relevant subject and environmental factors (e.g., age, type of hearing loss, fluency, noise type)	24 normal-hearing and 72 hearing-impaired adults	Quiet, white noise and crowd noise at 85 dBA; speech at 80 and 90 dBA; with and without earplugs and earmuffs	Percent correct of PAL PB-50 words	Intelligibility decreased with speech-to-noise ratio and was poorer in crowd noise than white noise; hearing-impaired subjects performed worse; non-fluency with English decreased intelligibility by 10-20%
Baumann & Marston (1986)	Investigate the effect of wearing hearing protection on speech intelligibility	15 normal-hearing and 15 hearing impaired adults	85 dBA speech noise; speech at 0 dB S/N ratio; with and without earmuffs	California Consonant Test scores	Findings were similar to earlier studies; hearing-impaired subjects had greater difficulty understanding speech in noise
Pekkarinen et al. (1990)	Assess changes in speech perception with/without hearing protection in noise	193 normal-hearing young adults	60 and 85 dBA speech in quiet and white noise at 0, +5, and +10 dB S/N ratios; with and with-out earmuffs	Discrimination scores on sentences, words, and CVCV non-words	At high speech and noise levels (i.e., 85 dBA and 0 dB S/N ratio) speech recognition was better with than without earmuffs
Fernandes (2003)	Determine the influence of hearing protectors on speech understanding	25 normal-hearing young male adults	Ears open, earplugs, earmuffs; pink noise at 60, 70, 80, and 90 dBA; speech at -10 to +10 dB S/N ratio	Percentage of correctly heard monosyllabic words	Findings were similar to earlier studies; hearing protectors decreased intelligibility in quiet and increased intelligibility in noise

Table 4 (continued).

Study	Research Objective	Subjects	Indep. Variables	Dependent Variables	Relevant Findings
Plyler & Klumpp (2003)	Evaluate communication ability in noise using hearing protection	14 normal-hearing young female adults	Speech at 75 and 90 dB SPL; ears open and earplugs	HINT test results (sentence SRT in terms of S/N ratio)	Communication ability was significantly better with hearing protection compared to the un-occluded condition
Dolan & O'Loughlin (2005)	Determine how different brands of earmuffs compare in terms of speech intelligibility for hearing-impaired listeners	10 adults with bilateral hearing loss	85 dBA industrial noise; ears open and with earmuffs	HINT test results (sentence SRT in terms of S/N ratio)	No difference between occluded and un-occluded with hearing-impaired subjects – these findings were similar to Rink (1979), but other studies indicated that hearing-impaired subjects performed worse

2.5.3 Talker effects

As previously discussed, most of the existing studies focused on the hearing protection user listening to speech; however, even some of the earliest research mentioned the fact that wearing earplugs may cause the person talking to change his/her speaking patterns. For example, Kryter (1946) pointed out that plugging the talker's ears caused a drop of one to two decibels in voice level. He reported slightly lower speech recognition scores when the talkers wore earplugs, and the previously mentioned advantage gained when listeners wore hearing protection in noise did not occur (when both the talker and listener wore earplugs) until the noise levels were higher. These findings can be attributed to how speech is produced and how sound waves behave in the external ear canal. When a person is speaking, the vibration of the vocal folds (as filtered by the oral and nasal cavities) produces very high levels within the vocal tract, and causes the tissue and bone of the skull to vibrate. When unoccluded, the ear canal acts as a high-pass filter, so sound generated from vibration of the ear canal walls is allowed to radiate out of the ear. When the ear canal is sealed, bone-conducted sound below 2000 Hz is more efficiently transmitted to the eardrum. Therefore, lower frequency sounds will be heard louder, and the intensity required to find bone-conduction thresholds is lowered when the ear canal is occluded (Watson & Gales, 1943). Zwislocki (1957) referred to this as the earplug effect, although it is usually called the occlusion effect by audiologists.

The occlusion effect causes a perceived change in one's own voice quality. It is often used as a subjective test to verify the fit of a hearing protector. The wearer is told that his/her own voice should sound deeper, hollow, or muffled when the hearing protector is seated properly. Zwislocki (1953) showed that a deeply inserted earplug occluding the bony part of the ear canal will reduce the occlusion effect. Berger and Kerivan (1983) fully describe how the occlusion effect changes as a function of the occluded volume. This effect is greatest when the ear canal is sealed right at the entrance. Less occlusion effect occurs with deep insertion of an earplug or, at the other extreme, when there is a large space around the auricle enclosed by a circum-aural earmuff. The occlusion effect is especially prominent when producing closed vowels such as /i/ and /u/, which can cause very intense low-frequency noise levels in the ear canal when an earplug is worn (Killion, Wilber, & Gudmundsen, 1988).

When discussing conductive hearing loss, textbooks (e.g., Sataloff, 1966, p.26) mention that the resulting occlusion effect affects vocal production exactly opposite from the Lombard effect, since one of the most noticeable consequences of a conductive hearing loss is that people tend to talk softer since they hear their own voices louder than usual. However, people are usually heard speaking louder when wearing hearing protection in a quiet environment. A theory to explain this is that the talker is monitoring his/her voice primarily via air-conduction and is attempting to overcome the attenuation of the air-conducted sound reaching his/her own ears, despite the fact that the bone-conducted speech is still amplified by the occlusion effect (Berger, 1988). No scientific studies have been reported in the literature that directly tests this theory.

As mentioned earlier, the first of two experiments reported by Howell and Martin (1975) suggested that a listener wearing hearing protection in noise levels above 85 dB will hear speech as well as or possibly better than without wearing hearing protection. They described the results from their second experiment as "…detracting somewhat from the optimism…" generated by the results of the first experiment. This comment was made in reference to the finding that talkers lowered their voices by 2.7 dB when wearing earplugs and by 4.2 dB when wearing earmuffs in a 93 dB broadband noise, and the listeners' average intelligibility scores decreased by 15% when the talkers wore earplugs and decreased by 25% when the talkers wore earmuffs. The authors indicated that the scores appeared to be lower than would be expected solely from a reduction in voice level. They suggested that persons wearing hearing protection speak less distinctly in addition to lowering their overall voice level.

In the following year, Martin, Howell, and Lower (1976) reported on another set of experiments designed to investigate the effect of hearing protection on communication, including the effects on the talker's voice. They observed a 2-3 dB reduction in voice level when the talker wore hearing protection, but did not find any significant differences in frequency content. Subtle changes in voice quality (which were not detected in their frequency analysis) were suspected to be the cause, so they conducted a final experiment to investigate this finding. This was accomplished by using recordings of eight talkers with and without earplugs in a background of 87 dBA. Noise was mixed in to produce a 3 dB signal-to-noise ratio, and the recordings were played to a panel of four subjects at approximately 70 dB SPL. No significant difference in intelligibility between the protected and un-protected talkers' speech was found, which they explained as no significant change in voice quality due to the talker wearing earplugs.

Hormann, Lazarus-Mainka, Schubeius, and Lazarus (1984) used 180 talker/listener pairs of normal-hearing subjects to test four different conditions: talkers with/without hearing protection and listeners with/without hearing protection. They were interested most in evaluating what happens when a talker and listener are sitting face-to-face and trying to carry on a conversation against a pink noise masker while both individuals are wearing hearing protection. When the background noise level was 92 dBA talkers spoke 4 dB softer while wearing foam earplugs. The authors also measured speaking time and found that words were spoken approximately 20% faster when earplugs were worn. Speech intelligibility results indicated significantly less was understood when both talkers and listeners were wearing earplugs.

Casali, Horylev, and Grenell (1987) reported on a pilot study designed to set speech levels for a large-scale study on speech communication with hearing protection in noisy environments. Eight subjects with normal hearing were instructed to read a list of words so that they would be intelligible to a listener seated in the same environment. In addition to testing in quiet, two industrial-type noises were played through loudspeakers at 60 and 83 dBA. The authors found that as the ambient noise level increased, the talkers' voice levels also increased at one-half the rate of the noise level increase, both with and without hearing protection. They also found that the talkers' voices increased while wearing hearing protectors in the no-noise condition, and the occlusion effect caused their speech levels to decrease in the highest noise condition (as compared to the unoccluded condition). To counteract the occlusion effect, the authors noted that individuals would have to make a conscious and unnatural effort to speak loud enough to be understood in high background noise levels, and suggested that training workers to do so would be difficult.

The next study reported in the literature (Navarro, 1996) found little or no difference between vocal output with ears covered versus ears uncovered. This study was conducted to examine the effect of ear canal occlusion and masking noise on several acoustical parameters of voice. Using 12 normal-hearing adult subjects, the fundamental frequency and overall sound pressure level were measured with the subjects' ear canals open and while occluded with foam earplugs. An average decrease of 0.73 dB was observed in the occluded condition, which represented a statistically (but not practically) significant change. These findings suggest that wearing earplugs does not have an effect on vocal production; however, the amount of occlusion (in this case, as defined by the attenuation) provided by the earplugs was extremely variable across subjects in this study, with some subjects receiving 0 dB at one or more test frequencies.

A more recent study by Tufts and Frank (2003) was conducted to obtain sound pressure level measurements of connected speech produced by talkers with ears open and while wearing two types of earplugs. The underlying factors in this experiment were to help evaluate the validity of noise-exposed workers' complaints and provide some information regarding the optimal selection of a hearing protector for a particular work environment. Similar to the Navarro (1996) study, Tufts and Frank (2003) found a 0.6 dB decrease in speaking level when earplugs were worn in quiet. Overall, the findings of this study suggest that wearing earplugs caused the undesirable effect of lowered overall vocal levels and speech-to-noise ratios as compared to the ears-open condition. Therefore, less speech information would be provided to listeners when the talkers wore hearing protection, and speech communication would be negatively affected.

Table 5 summarizes the studies reporting on the effects of ear canal occlusion and/or noise on a talker's voice production when hearing protection is worn.

Table 5. Research involving the occlusion effect and vocal production when hearing protection is worn.

Study	Research Objective	Subjects	Indep. Variables	Dependent Variables	Relevant Findings
Kryter (1946)	Assess speech intelligibility in noise while wearing earplugs	8 males	Quiet, 75, 85, 95, and 105 dB submarine engine room noise; earplugs, ears open	Speech output level	In quiet, talkers' voice level was raised 3-4 dB; in noise, voice levels dropped 1-2 dB
Zwislocki (1957)	Determine free-field bone-conduction thresholds	6 adults	MAF testing with and without earplugs	Hearing thresholds	When not inserted too deeply, earplugs increase bone conducted sound; referred to as the earplug effect
Zwislocki (1953)	Investigate the mechanisms for inter-aural attenuation	3 (no details provided)	Testing with and without an earplug in one ear	Inter-aural hearing threshold differences	A deeply inserted earplug occluding the bony part of the ear canal will reduce the occlusion effect
Berger & Kerivan (1983)	Determine the influence of the occlusion effect during hearing protector attenuation testing	4 male and 2 female normal-hearing adults	6 hearing protectors causing low to high occluded volumes	Microphone-in-real-ear measurements; bone conduction thresholds	Maximum occlusion effect occurred when ear canal is closed at the entrance; minimum occlusion effect at lowest or highest occluded volumes
Howell & Martin (1975) and Martin et al. (1976)	Investigate the effect of wearing hearing protection on speech intelligibility	4 normal-hearing male university students	Quiet, 67-95 dB SPL broadband noise; ears open, earplugs, and earmuffs	Speech output level	Wearing hearing protection in noise caused the talker to lower his/her voice level and possibly speak less distinctly
Hormann et al. (1984)	Investigate the effect on speech intelligibility when both the talker and the listener are exposed to the same noise level and are wearing hearing protection	360 normal-hearing university students	Pink noise at 76, 84, and 92 dBA; all combinations of talker and listener with/without earplugs	Speech output level; speaking rate; pause length	Results were similar to Kryter (1946) and Howell & Martin (1975); talkers spoke softer when earplugs were worn

Table 5 (continued).

Study	Research Objective	Subjects	Indep. Variables	Dependent Variables	Relevant Findings
Casali et al. (1987)	Investigate the effects of earmuff occlusion and ambient noise on a talker's voice intensity	4 males and 4 females with normal hearing	Quiet, white noise, low frequency industrial noise, and high frequency industrial noise at 60 and 83 dBA; ears open, earmuffs	Speech intensity levels	Findings were similar to previous research; as the ambient noise level increased, talkers' voice levels increased at one-half the rate of the noise level increase, both with and without hearing protection; talkers' voices increased while wearing hearing protectors in the no-noise condition, and the occlusion effect caused their speech levels to decrease in the highest noise condition
Navarro (1996)	Examine the effect of ear canal occlusion and masking noise on voice output	4 normal-hearing male adults and 8 normal-hearing female adults	Ears open, earplugs, 105 dB SPL speech noise	Intensity level; fundamental frequency	Unlike previous studies, the author reported that ear canal occlusion did not significantly affect vocal output, although the presence of noise did
Tufts & Frank (2003)	Assess the effects of wearing hearing protection on speech production	16 males and 16 female adults with normal hearing	Quiet, 60, 70, 80, 90, and 100 dB SPL pink noise; ears open and with earplugs	Overall and 1/3-OB speech intensity levels	In quiet, hearing protectors caused a slight decrease in speech level (similar to Navarro, 1996); talkers lowered their voice level in noise when hearing protection was worn

2.6 ADDITIONAL CONSIDERATIONS FOR SPEECH INTELLIGIBILITY

2.6.1 Self-hearing

The ability to hear one's self is an essential component of successful speech communication. One of the earliest investigations into the phenomenon of self-hearing was described by von Bekesy in 1949. He was interested in the physical characteristics of the middle ear that permitted a listener to hear external environmental sounds while minimizing the perception of any self-generated sounds such as chewing, swallowing, etc. When a person speaks, that individual hears him/herself both via air conduction and bone conduction. Through his experiments, von Bekesy (1949) determined that the air and bone conduction pathways produced sensations of approximately the same order of magnitude. During his years of extensive study of bone conduction, Tonndorf (1972) discovered that the bone conduction route was less effective at high frequencies than for lower frequencies. Therefore, a person would hear more of the low frequency components of his/her self-generated speech. This provides an explanation for the common observation that an individual's voice does not sound normal when a person listens to a recording of his/her own speech.

Other studies have supported the conclusion that bone conduction causes talkers to hear the lower frequencies of their own speech with more emphasis than what an external listener is hearing. Shearer (1978) conducted tests of subjects' hearing in the presence of the vowels /a/, /i/, and /u/ which were either vocalized by the subject during the test or were recorded and played back to the subject while the audiogram was taken. Overall, the amount of masking by the recorded vowels was greater than the amount produced by the vowel sounds vocalized by the subjects during the test. More specifically, the recorded vowels had a greater masking effect on the higher audiometric test frequencies while the lower audiometric frequencies were more effectively masked when the vowel sounds were produced live. The work by Porschmann (2000) agreed with the results of the earlier studies and suggested that bone conduction dominated the self-perception of a person's voice at frequencies between 700 and 1200 Hz. Much more recently, Reinfeldt, Ostli, Hakansson, and Stenfelt (2010) conducted a study to determine the bone-conduction relative to the air-conduction sensitivity for ten different phonemes. Their findings agreed with the earlier studies regarding the air and bone components being of equal importance, and also found the relative contributions of each pathway to be frequency dependent.

The term *autophonic response* has been used to describe the perceived loudness of a person's own voice (Lane, Catania, & Stevens, 1961). These authors assert that there is a significant difference between the perceived level of a self-produced sound and a sound that is generated by an external source. Essentially, this means that if a talker doubles his/her voice output, it will not necessarily sound twice as loud to a listener. Hearing acuity is primarily responsible for judging the loudness of external sounds, while vocal effort and other internal proprioceptive mechanisms influence how loud one's own voice sounds.

Maurer and Landis (1990) further explored the role of bone conduction on the self-perception of speech. They asked their study participants to mix their own separately recorded air- and bone-conducted speech until they recognized the voice as sounding the most familiar. Although most subjects added bone-conducted speech to the mixture, no significant correlation was found in the chosen mixture of bone/air-conducted speech, and there was a great deal of variability among subjects. These findings were reviewed by Shuster and Durrant (2003) who suggested that the bone vibration measurement techniques employed by Maurer and Landis (1990) were not sufficient to describe the transfer function involved in self-hearing. Subsequently, Shuster and Durrant (2003) reported on a two-part study in an effort to determine whether multi-band filtering of tape-recorded speech could be perceived as more natural sounding, and also to determine the overall frequency response of the self-monitoring of speech. First, they used a delayed auditory feedback paradigm and asked their participants to rate how much the delayed speech sounded like their actual voice. The delayed speech was processed through a 2/3 octave-band equalizer, and a variety of equalizer settings was used to produce differing amounts of low-pass filtering. This task was conducted twice; once with the researcher adjusting the equalizer, and again with the subject making his/her own adjustments. As expected, the subjects preferred some low frequency emphasis; however, no statistically significant differences in the ratings of the settings were found. In the second part of the study, subjects were instructed to identify whether recorded speech samples were produced either by themselves or by another speaker. Each of the subjects' recorded speech samples were played twice: first unfiltered and again with low-pass filtering using the same equalizer settings determined from the first part of the experiment to be in the middle of the preferred range. Thus, the participants had three response choices when listening to the recordings: (1) Me, but not as I sound to myself; (2) Me, as I sound to myself; and (3) Not me. The results showed that low-pass filtered speech sounded more like an individual's own speech (when produced live) than unfiltered speech. Unfortunately, the exact transfer function of self-hearing was not able to be determined. Shuster and Durrant (2003) suggested that more sophisticated digital filtering and a better computerized adaptive adjustment procedure might enable characterization of the transfer function. No further work on the mechanisms of self-hearing has been reported in the literature; however, several studies have recognized its applicability (e.g., Sugimori, Tomohisa, & Tanno, 2013; Heinks-Maldonado, Srikantan, & Houde, 2006; Ford & Mathalon, 2005). Such studies were primarily concerned with understanding auditory cortical responses, cognitive processes, auditory hallucinations, etc. In each case, the researchers employed low-pass filtering to render the auditory feedback closer to how the subjects' own voices would sound, or they at least recognized the potential effect this could have on their experimental design.

Another related consideration is the effect of the acoustic or middle ear muscle reflex. This refers to the contraction of the stapedius and tensor tympani muscles located within the middle ear space. The stapedius is attached to the head of the stapes, and the tensor tympani is attached to the manubrium of the malleus (Zemlin, 1981). When contracted, these muscles increase the middle ear impedance, thereby decreasing the efficiency of vibratory energy transmission through the ossicular chain (Borg, Nilsson, & Engstrom, 1983). The tensor tympani muscle has long been thought of as providing a protective role, although its general function in humans is still not completely understood (Mukerji & Lee, 2010). The tensor tympani muscle responds primarily to non-auditory events such as tactile stimulation of the face and eyes, or it may be activated as a part of the startle response (Klockhoff, 1961). It also may prevent overstimulation from self-generated noise, such as swallowing or vocalization (Stach, Jerger, & Jenkins, 1984). In humans, the stapedius muscle is more responsive to acoustic stimuli than the tensor tympani (Neergard, Andersen, Hansen, & Jepsen, 1964; Djupesland, 1964; Liberman & Guinan, 1998). Contraction of the stapedius muscle may enhance speech intelligibility by preventing the upward spread of masking, specifically the masking of speech by intense low-frequency environmental noise (Borg & Zakrisson, 1974, 1975; Phillips et al, 2002).

The stapedius muscle also may attenuate self-produced sound, which could reduce interference between self-produced sounds and external sounds (Shearer & Simmons 1965; Borg & Zakrisson, 1975). Regardless of the activation mechanism, the acoustic reflex results in attenuation of low-frequency ossicular chain vibration (Gelfand, 1981). This occurs because the middle ear muscles serve to stiffen the middle ear system; since stiffness is inversely related to frequency, the effect is most prominent at low frequencies (below 1000 Hz) and essentially negligible at the higher frequencies.

2.6.2 Prediction techniques

In addition to developing tests of speech intelligibility, early researchers were interested in developing techniques to predict the intelligibility of speech by analyzing its spectrum. French and Steinberg (1947) reported on the development of a method they called the Articulation Index (AI) which was based on physical and acoustical measurements of the communication environment. The basic concept of the AI was that the range of speech frequencies could be divided into 20 increments (bands) that provided equal contributions to the overall intelligibility. The range of possible AI values is from zero to one. Calculated AI values will not necessarily match the score obtained from any particular speech intelligibility test; instead, the AI may be considered as the proportion of the total number of speech cues available to the listener. An AI value of 0.0 indicates that none (i.e., 0%) of the speech cues reach the listener, while an AI value of 1.0 indicates that all (i.e., 100%) of the speech cues are available to the listener. Similarly, a value of 0.5 represents half (50%) of the speech cues reaching the listener. Kryter (1962a,b) reported on usage and validation studies of the AI, which was subsequently issued as the American National Standard Methods for the Calculation of the Articulation Index (ANSI, 1969). A few studies were conducted specifically to investigate the validity of using the AI as a predictive method for speech intelligibility while wearing hearing protection with varying degrees of success (e.g., Wilde & Humes, 1990; Gower & Casali, 1994).

The Articulation Index was revised and renamed the Speech Intelligibility Index (SII; ANSI S3.5-1997, R2012). Several factors in the model were updated to reflect research findings since the AI was first developed. Currently, the SII methodology accounts for variables such as external masking noise, differences in vocal effort, reverberation, monaural/binaural listening, hearing loss, varying message content, and the effect of wearing hearing protection. While the SII is adaptable to different listening conditions, it is important to remember that speech intelligibility predictions are correct only for an average group of talkers/listeners, and not individual persons.

Research is still being conducted to improve existing speech intelligibility prediction methods as well as to develop new techniques. Rhebergen, Versfeld, and Dreschler (2006, 2008) have developed an extension to the SII, which they call the Extended Speech Intelligibility Index (ESII) model. This was introduced to account for the fact that the SII cannot predict intelligibility in fluctuating noise. A new model was proposed by Musch and Buus (2001a,b) that uses statistical decision theory to predict speech intelligibility. Their model is called the Speech Recognition Sensitivity (SRS) model, and is intended to account for synergistic interactions between speech bands that are not adequately explained by the SII.

2.6.3 Clear speech/Speech training

Another talker-related characteristic that can affect speech intelligibility is whether the person talking correctly enunciates his/her speech. Picheny, Durlach, and Braida (1985) studied the effects of conversational versus clear speech on hearing-impaired listeners. Conversational speech samples were obtained by instructing the talker to recite a list of sentences in the same manner in which he spoke in ordinary conversation. Clear speech recordings were made by having the talker speak "…as clearly as possible, as if he were trying to communicate in a noisy environment or with an impaired listener." An average improvement in intelligibility scores of 17% was found with the clear speech sentences. A follow-on article (Picheny, Durlach, & Braida, 1986) indicated that clear speech was spoken more slowly, stop bursts and word-final consonants are released, and obstruents were produced louder, although changes in the long-term spectrum were small. The authors noted that speaking clearly was not equivalent to simply increasing the high frequency speech sounds. More recent research shows that speaking slowly is not solely responsible for better intelligibility with clear speech and talkers may employ different strategies to produce clear speech (Krause & Braida, 2004; Liu & Zeng, 2006).

Clear speech is similar to hyper-articulated speech, which is purposely spoken to ensure intelligibility. By contrast, hypo-articulated speech is similar to conversational speech, where context or message familiarity is relied upon for complete understanding, possibly at the expense of accurate pronunciation. Together, hyperspeech and hypospeech comprise the H & H theory, which suggests that speaking styles are adjusted to match the particular communication situation (Lindblom, 1990). Kain, Amano-Kusumoto, and Hosom (2008) reported on work that will lead to a better understanding of which specific acoustic features are relevant for the improved intelligibility of clear speech. These efforts will enable the development of a model that quantifies the inter-relationships between acoustic features of speech and resulting intelligibility. Their intent is to apply this knowledge to hearing aids and other assistive listening devices, enabling the outputs of these devices to transform ordinary conversational speech into an approximation of clear speech.

Individuals with Parkinson's disease are difficult to understand due to their dysarthric speech patterns. Treatment for dysarthria typically focuses on increasing vocal loudness, rate control, and prosody/suprasegmental aspects (Yorkston, Hakel, Beukelman, & Fager 2007). The Lee Silverman Voice Treatment (LSVT) is an intensive behavioral speech treatment designed to improve the perceptual characteristics of voice by increasing respiratory/phonatory effort, thereby increasing loudness (Ramig, Countryman, Thompson, & Horii, 1995; Fox, Ramig, Ciucci, Sapir, McFarland, & Farley, 2006; Sapir, Spielman, Ramig, Story, & Fox, 2007). Goals of LSVT interventions are to increase phonatory effort, vocal fold adduction, and respiratory support. Changes in loudness as well as other aspects of speech production such as articulatory precision have been demonstrated with LSVT treatments.

Listener-related characteristics other than hearing ability may have an effect on speech intelligibility in noise while wearing hearing protection. For example, auditory training has been used to improve the communication performance of hearing aid and cochlear implant users (Sweetow & Palmer, 2005; Burk, Humes, Amos, & Strauser, 2006; Burk & Humes, 2007). Application of these types of techniques specifically for use by noise-exposed industrial workers has not been reported in the literature.

A well-known but perhaps subconscious method to increase speech intelligibility in noisy conditions is simply allowing the listener to see the talker's face (Sumby & Pollack, 1954; Miller & D'Esposito, 2005; Ross, Saint-Amour, Leavitt, Javitt, & Foxe, 2007). Face-to-face communication permits speech/lip-reading, and integrating the visual and auditory information will generally aid a listener's understanding ability. The most recent research in this area indicates that improvement is not necessarily the greatest when auditory input is weakest; instead the maximal benefit provided by visual cues occurs at intermediate signal-to-noise ratios (Ross, et al., 2007). One situation where the auditory and visual cues together do not combine to provide increased intelligibility is described by the McGurk effect (McGurk & MacDonald, 1976). In laboratory experiments, these investigators demonstrated that the interference of a phoneme and an incongruent viseme can be strong enough to create an illusory percept.

2.7 ANALYSIS AND SUMMARY OF THE EXISTING RESEARCH

Noise-induced hearing loss is virtually always preventable if suitable hearing protection is used. However, many individuals refuse to wear hearing protection because they say it interferes with normal speech communication (Svensson, Morata, Nylén, Krieg, & Johnson, 2004; Helmkamp, 1986). This is somewhat perplexing, since research has shown that wearing hearing protection does not prevent normal-hearing individuals from understanding speech in noise levels above 85 dBA, and normal-hearing workers may actually hear speech better when wearing earmuffs or earplugs in a noisy work environment (Kryter, 1946; Howell & Martin, 1975; Lindeman, 1976; Rink, 1979; Chung & Gannon, 1979; Abel et al., 1982; Bauman & Marston, 1986; Pekkarinen et al., 1990; Nixon & Berger, 1991; Klumpp, 2003; Fernandes, 2003). Nevertheless, workers will often remove their hearing protectors to communicate with co-workers. In some cases, this may be explained by research that shows speech intelligibility in noise (while wearing hearing protection) to be worse for hearing-impaired persons than for normal-hearing individuals (Chung & Gannon, 1979; Bauman & Marston, 1986). Other explanations/rationalizations for these communication complaints must exist. Alternatively, there may be a different reason for rejecting hearing protectors, such as hearing protectors are uncomfortable to wear (for a review see Davis, 2008), or some other physiological or psychological factor.

Data regarding the effects of a particular hearing protector on speech intelligibility are not available from the manufacturer, and on-site safety or hearing conservation program managers typically do not have access to the necessary instrumentation for the measurement of speech intelligibility. Currently, hearing protectors are selected according to the labeled Noise Reduction Rating (NRR) or worker preference (likely related to the degree of comfort), or they are simply chosen from the available supply of employer-provided earplugs. Speech intelligibility has been identified as an important issue among hearing conservation professionals (Stephenson, 2009), but without the benefit of knowing to what extent each device affects speech intelligibility for a given acoustic environment (and employee's hearing status), potential communication issues cannot be identified when hearing protectors are selected.

The Lombard effect is known to influence the way people talk when background noise is present. Intuitively, it may seem plausible to assume that the acoustical properties of Lombard speech are identical to loud speech produced in a quiet setting. However, research has shown that Lombard speech is more intelligible than loud speech intentionally produced in quiet conditions (e.g., Summers et al., 1988). Additionally, the results of studies such as Letowski et al. (1993) suggest that Lombard speech is acoustically different from loud speech produced in quiet. Effects of these vocal changes on speech intelligibility (and potential vocal stress/strain) as experienced by noise-exposed workers in their everyday working environments remain largely unexplored. The actual effects – whether beneficial or detrimental to effective communication – are unknown, since the majority of the studies of Lombard speech were carried out in controlled laboratory conditions which did not involve spontaneous speech. A study by Patel and Schell

(2008) used relatively spontaneous speech, and found that linguistic content influenced the extent of the Lombard effect. In 90-dB multi-talker noise, information-bearing words were elongated more than other less important words. The implication would be that it may not be valid to generalize the results of speech intelligibility tests when the speech (i.e., recorded stimuli or spoken by a live talker) was produced in quiet or under a different background noise level than the subject's listening condition. None of the commercially available pre-recorded tests use speech from talkers while they were in a background of noise or while wearing hearing protection.

Numerous studies involving speech intelligibility in noisy conditions have been conducted, primarily to investigate the effects of hearing impairment or the acoustical characteristics and performance of hearing aids. The majority of these studies focused on non-hazardous background noise levels, i.e., those that are sufficient to interfere with speech communication but not so loud as to cause noise-induced hearing loss. Workers would not be wearing hearing protection in those situations; therefore, the findings may not be applicable or transferable to actual hazardous noise working conditions. Unfortunately, some of the studies specifically conducted to evaluate hearing protection did not use realistic (i.e., above 85 dBA) background noise levels. For example, Reeves (1998) attempted to develop a hearing protector selection method where speech intelligibility would be a selection parameter. He performed listening experiments with speech at different signal-to-noise ratios using low-, mid-, and high-frequency emphasis noises. Presentation levels were chosen to prevent ceiling effects in the normal-hearing listeners' data, thereby creating a more sensitive test of speech intelligibility. However, the maximum noise levels (62 dBA for low- and 67 dBA for mid/high-frequency emphasis noise) were well below the level at which hearing protectors would typically be worn.

Several other studies suffered from this same limitation and were not included in this review (e.g., Kjukaanniemi & Sorri, 1988; Abel, Armstrong, & Gigure, 1993; Abel & Spencer, 1997).

As reviewed above in sections 2.2 through 2.6, several studies involving the effect of hearing protectors on speech intelligibility have been conducted. In each case, one or more devices were evaluated by some type of speech recognition test. Clinical audiologists are most familiar with word discrimination testing in quiet, which is not likely to be indicative of an individual's performance on a speech test while wearing hearing protectors and being subjected to high levels of background noise. Widening the choice of test material to sentences or connected discourse seems like a reasonable approach. This opens up numerous additional concerns, such as the effect of semantic/contextual cues that can enhance the recognition of a particular word in one context while preventing the same word from being heard correctly when presented in another context. Miller, Heise, and Lichten (1951) were among the first researchers to study these issues. One of their findings was that the signal-to-noise ratio (SNR) for 50% recognition (i.e., threshold testing) changed depending on whether digits, words, or nonsense syllables were used in the test. The concept of scoring in terms of SNR loss rather than the traditional percent correct has been incorporated into the newer speech tests. Unfortunately, the relationship between scores on the various types of speech intelligibility tests is unknown, since only a few studies have been conducted specifically to compare different speech-in-noise tests (McArdle, Wilson, & Burks, 2005; Wilson, McArdle, & Smith, 2007).

Even if all existing speech-in-noise tests were found to yield equivalent results, they do not necessarily provide insight into identifying which hearing protectors might be better for a particular individual in a given noise/communication situation. Cluff, Pavlovic, and Overson (1993) recognized two important limitations with existing speech intelligibility tests. First, the acoustical characteristics of speech produced in a noisy work environment will be different from the recorded speech material found on commercially available tests. Second, non-acoustic factors such as linguistic structure and message content/predictability are quite different between pre-recorded tests and actual workplace communications. In their article, the authors primarily addressed the second issue, and reported on the development of a speech intelligibility test designed for use in an industrial workplace. They solicited 3- to 5-syllable phrases from individuals employed in noisy workplaces, and created eight 20-phrase phonetically balanced lists of phrases that were “loosely assumed” to be typical of on-the-job communication in various industries. Regarding the first issue of acoustical differences, the phrases were recorded by a talker speaking at near-maximum vocal effort without wearing hearing protection in a quiet audiometric booth. Unfortunately, studies that used this test or further research into its underlying concepts were not found in the literature.

The presence of an occlusion effect and the Lombard effect for talkers wearing hearing protection has yielded conflicting results between studies. Kryter (1946) and Casali et al. (1987) reported that talkers raised the level of their voices by approximately 4 dB when they wore hearing protection in quiet. Conversely, Navarro (1996) and Tufts and Frank (2003) reported slight (less than 1 dB) decreases in voice level in the same condition. The explanation for these different findings is unknown. It appears that the magnitude of either the occlusion effect and/or the hearing protector attenuation must have been different to cause the different findings. Navarro (1996) indicated that the earplugs worn by his subjects provided adequate protection since the average attenuation values were consistent with data reported elsewhere. However, his data show that the range of attenuation values was 0-35 dB for two of the frequencies (250 and 2000 Hz), and the measured attenuation at 500 and 1000 Hz was also extremely variable (10-30 dB and 5-35 dB, respectively). Thus, some of the subjects did not receive any attenuation (at least at the lower frequencies), and their data were not actually representative of someone wearing hearing protectors. In the case of little or no difference between occluded and un-occluded speech levels in quiet, Tufts and Frank (2003) suggested that shallow insertion of the earplugs caused the attenuation of the air-conduction component and the enhancement of the bone-conduction component of the subjects' speech to offset one another. No further experiments were conducted to isolate the contributions of ear canal occlusion and reduction of the airborne sound.

To summarize, there are many aspects related to fully understanding verbal communication between noise-exposed workers that are wearing hearing protection. The extent of the effects caused by wearing a hearing protector and while being subjected to high noise levels has not been fully explained in the literature. One part of this discussion centers around how the occlusion effect and attenuating the sound of a person's voice reaching his/her ears generally produce opposite effects on that individual's vocal output. As described in the following sections, a carefully controlled laboratory study was devised to systematically examine these issues. Although overall voice level alone does not provide all of the necessary clues, quantifying this component will provide insight into one aspect of the problems encountered when attempting to communicate in hazardous noise conditions.

3.0 RESEARCH QUESTION AND METHODS

3.1 OBJECTIVE

The intent of this project was to investigate acoustic changes in speech characteristics that occur when producing speech while wearing hearing protection in noisy environments. As indicated above, the primary factors are the occlusion effect and the attenuation provided by hearing protectors.

Based on an analysis of the gaps and inconsistencies in the knowledge in this area, the following research questions were posed: What is the effect on voice output level when the attenuation provided by a hearing protective device worn by an individual is carefully controlled? Next, if changes in speech output are observed when hearing protection is worn, which mechanism – ear canal occlusion or hearing protector attenuation – has a greater effect on an individual's voice output level?

In addition to providing a basis for future work involving speech intelligibility testing, this project has other practical implications. Speaking with a lowered voice level could have an adverse effect on the intelligibility (i.e., understanding) experienced by the intended listener in a background of noise. If a talker consistently lowers his/her speech level due to the occlusion effect, then individuals that must be heard and understood in a noisy environment should be instructed to wear hearing protectors that reduce/minimize this effect. If the attenuation provided by the hearing protector is what causes an individual to change his/her vocal output, then very careful selection of the best hearing protector for a particular noise environment is necessary, in order to provide adequate attenuation (protection) while promoting optimal speech production.

3.1.1 Hypotheses

The hypotheses to be tested were derived from previous studies described in the literature that revealed conflicting results. The following null hypotheses were tested in an effort to advance the knowledge base and provide information to better understand how speech production is influenced by wearing hearing protection:

Hypothesis #1 Ear canal occlusion does not produce a change in a person's voice output level when hearing protectors are worn and background noise is present.

Hypothesis #2 The attenuation provided by a hearing protector does not produce a change in a person's voice output levels when hearing protectors are worn and background noise is present.

3.2 STUDY PLAN

3.2.1 Approach

The purpose of this study was to assess the effect of ear canal occlusion and hearing protector attenuation (in different background noise levels) on the overall level of a talker's vocal output. To test whether differences in vocal characteristics are due solely to the occlusion effect, speech produced while subjects' ear canals were occluded was measured without the subject receiving any attenuation from the hearing protectors. To achieve this condition, the subject's own voice was reproduced (in real-time) through a set of headphones, essentially restoring the same sound level reaching his/her ears as when the hearing protectors are not worn (i.e., the attenuation of the protectors is being offset). To test whether vocal output differences are due to the reduction in the talker's self-perceived voice level, the amount of occlusion was held constant while changing the effective hearing protector attenuation.

The study design relied on independently controlling the amount of effective attenuation for different occlusion effect conditions. This was accomplished by assembling an "air-conduction voice feedback restoration system" that consists of a microphone, a graphic equalizer, an amplifier (headphone driver), and a set of stereo headphones. The purpose of the air-conduction feedback restoration system was to offset the attenuation of the hearing protectors. Subjects' own voices were picked up by the microphone, amplified by a specified amount, and played back through the headphones to simulate different amounts of effective attenuation, including 0 dB.

3.2.1.1 Voice feedback system instrumentation

A schematic diagram of the air-conduction restoration system is shown in Figure 1. Instrumentation for this system consisted of an Earthworks SR78 hypercardioid microphone connected through its companion LAB 101 preamplifier to an Ashly NE4400 digital signal processor.

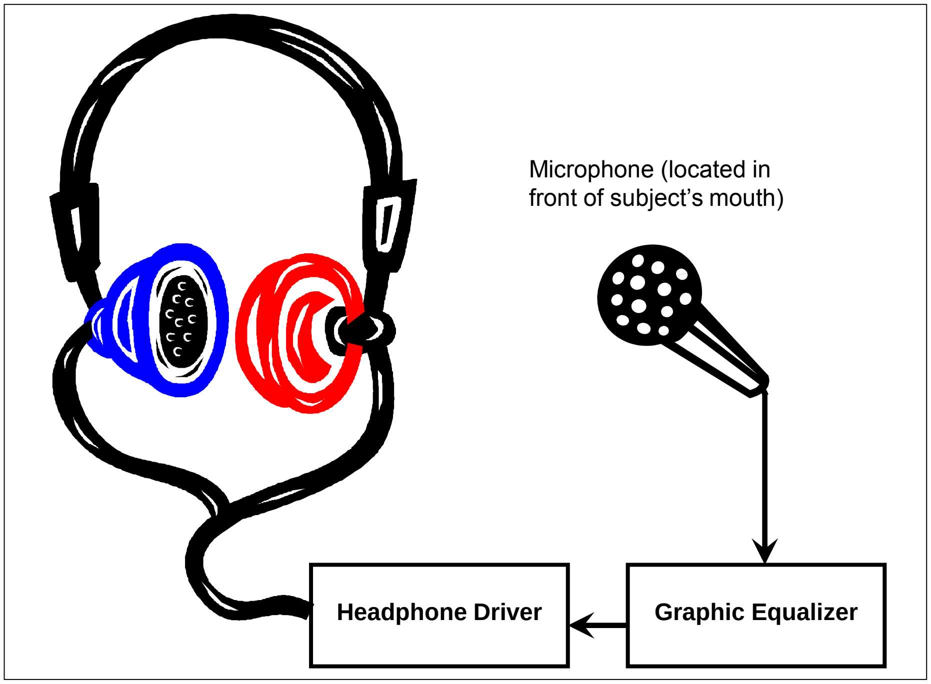

Figure 1. Air-conduction feedback (voice restoration) system.

The signal processor was configured as a dual-channel 31-band graphic equalizer running at a 96 kHz sampling rate and 24-bit resolution. Individual adjustments of ±15 dB in each one-third octave-band can be made with the graphic equalizer function. Overall performance characteristics include a frequency response of 20 Hz to 20 kHz (±0.25 dB), a dynamic range of >114 dB, and total harmonic distortion of <0.002%. An Ethernet connection to a laptop computer was used to change settings on the signal processor.

The output of the signal processor was directed to a Rane HC-6S headphone amplifier and Sennheiser model HDA 200 audiometric headphones. These headphones are routinely used for extended high-frequency audiometric testing, and have a frequency response of 20 Hz to 20 kHz. The headphones were modified slightly by inserting a custom-molded one-half inch thick solid plastic spacer between each earcup shell and cushion. This modification extends the earcup further away from the wearer's head and eliminates any possibility of the headphone interfering with an earplug when one is worn underneath. Additionally, the added room under the earcup effectively increases the volume of enclosed air, thereby partially offsetting the space taken up by the transducer.

As an aside, the initial plan was to use Sennheiser model HD 800 headphones instead of the HDA 200 headphones. The HD 800 headphones employ an "open-back" design to lessen the feeling of isolation (and the occlusion effect) to the wearer. As illustrated in the next section, using the HDA 200 "closed-back" headphones for the voice feedback system was a necessary compromise when earplugs were used to occlude the subjects' ear canals.

3.2.1.2 Evaluation of voice feedback instrumentation

Preliminary testing found that an open-back headphone was not feasible, and the HDA 200's hard earcup shells and snug fit were necessary to reduce the leakage of sound from the headphones and avoid an acoustic feedback loop. Figure 2 confirms that this was not an unrealistic compromise. This graph illustrates that the occlusion effect did not change when measured with the earplugs alone and then measured again with the HDA 200 headphones covering the subject's ears. The occlusion effect produced by the earplug was far more dominant than any effect of the headphone. This finding is consistent with previous research that indicated if the volume of trapped air under an earmuff is large enough, then the occlusion effect is negligible (Stenfelt & Reinfeldt, 2007). This was verified on each subject by repeating the occlusion effect measurement (described later in section 3.2.2) while wearing the HDA 200 headphones over the earplugs (with the headphones unplugged).

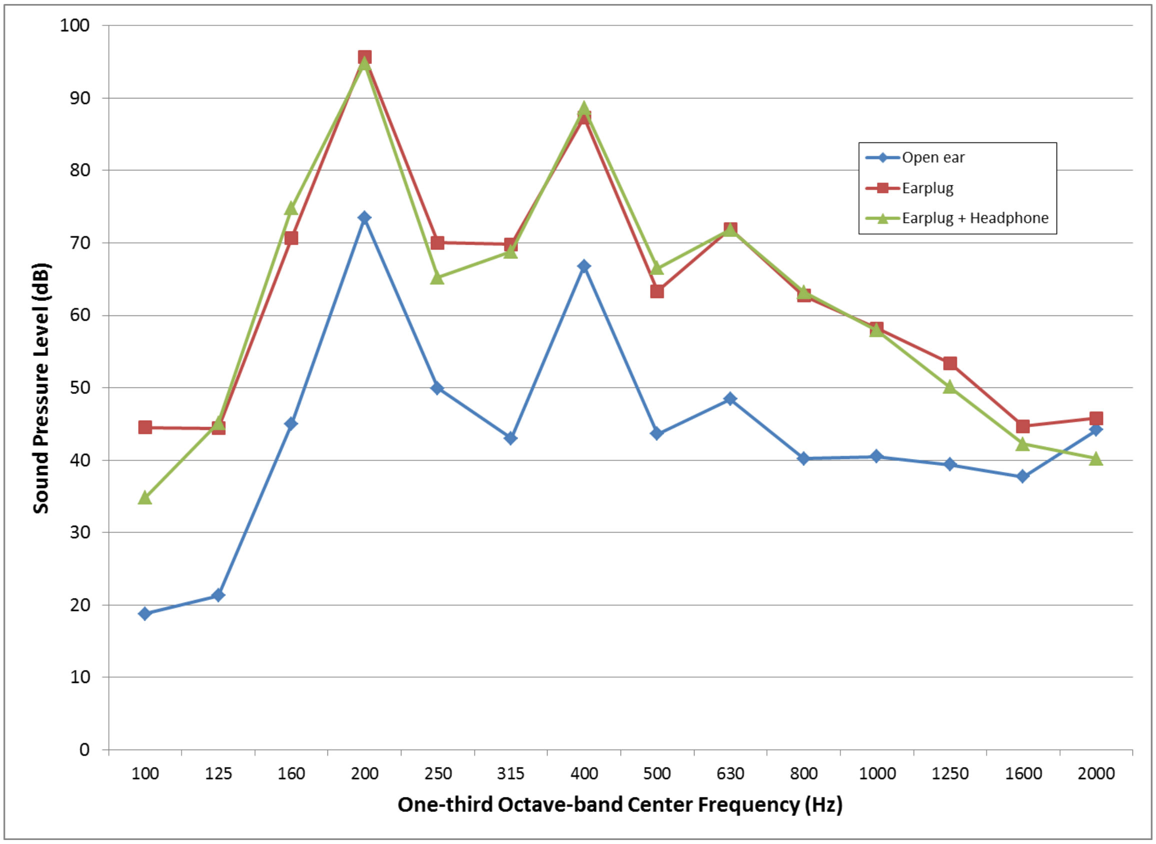

Figure 2. Example of ear canal measurements during sustained vocalization of /i/.

The air-conduction feedback system also was tested to determine the amount of delay between the arrival of a signal at the microphone and the delivery of the signal through the headphones. A delay of more than 15 msec would likely be perceived by the subject as an annoying echo, and would interfere with conducting the experiment (Stone & Moore, 2002). An evaluation was conducted by placing the input microphone into a hearing aid test chamber and playing one-third octave-bands of noise from 125 Hz to 8000 Hz through the chamber's loudspeaker. A KEMAR manikin was used to measure the headphone output. The cross-correlation was computed between the input (microphone) and output (headphones). This is a measure of the similarity of two signals as a function of a time-lag applied to one of them. The propagation delay through the system was determined by where the peak occurred. A peak at 0 msec would mean that the there was no delay between the input and the output. The graph in Figure 3 illustrates the cross-correlation results for the 1000 Hz one-third octave-band. Cross-correlation results indicated that delays of less than 2 msec would be introduced across all frequencies and for both the right and left earphones.

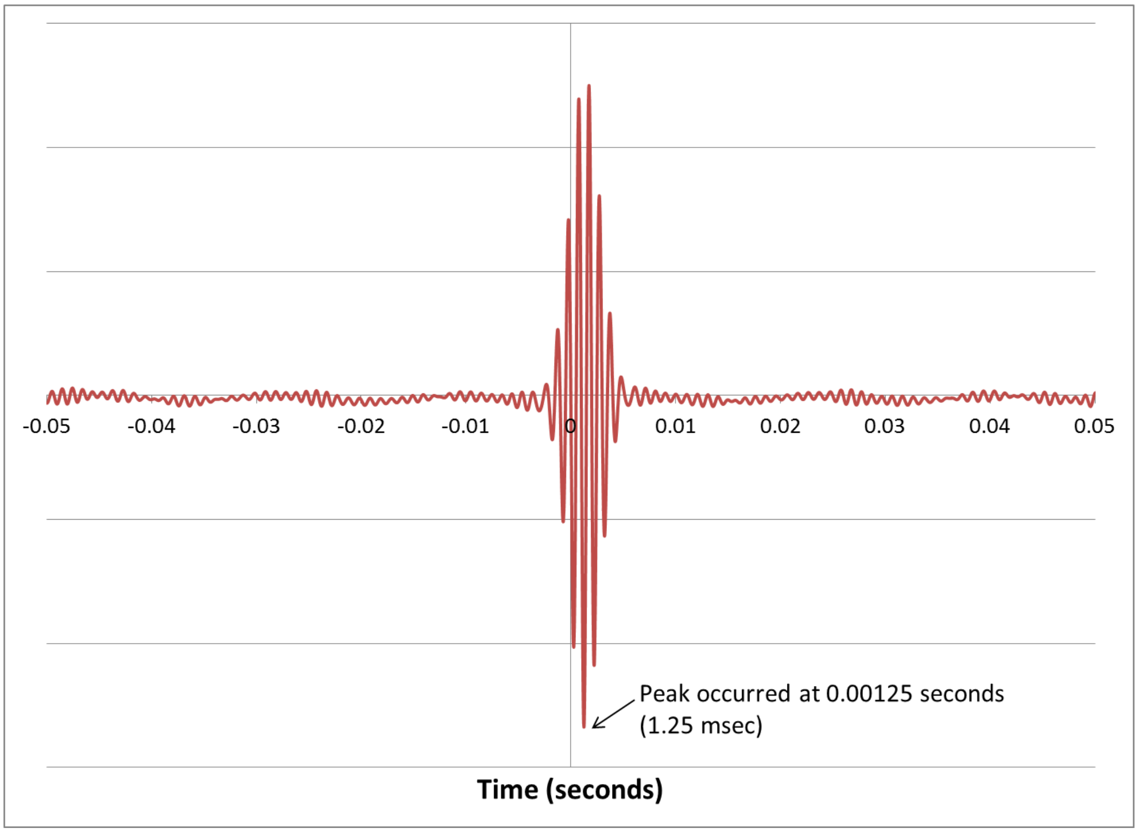

Figure 3. Cross-correlation at 1000 Hz; input microphone vs. right earphone.

Calibration of this system was accomplished by playing a broad-band noise through a G.R.A.S. Sound & Vibration Type 44AA Mouth Simulator (loudspeaker) and using a separate measurement microphone and acoustic analyzer to identify the correct settings for the voice feedback system. The mouth simulator was placed on a stand in a quiet room, adjacent to a double-walled audiometric booth. White noise was played at 65 dB through the mouth simulator with the measurement microphone and voice feedback microphone placed side-by-side five inches away. The voice feedback headphones were worn by a KEMAR manikin located inside the booth. Acoustically separating the KEMAR measurement system from the mouth simulator was necessary to prevent the manikin from directly picking up the sound from the mouth simulator. The overall level of the voice feedback system was adjusted until the KEMAR reading matched the measurement microphone level. This defined the unity gain setting, i.e., where the level was exactly the same under the voice feedback system headphones as it was directly in front of the mouth simulator. This established the reference point or 0 dB attenuation condition. From here, the overall level of the voice feedback system could be varied by a precise amount (e.g., 10, 20, or 30 dB) to simulate different amounts of hearing protector attenuation.

Ideally, the voice feedback system's microphone should be placed as close as possible to the subjects' ear. This would ensure that the input to the microphone would be virtually identical to the amount of the self-generated speech signal reaching the subjects' ear canal via air-conduction. However, this was not practically possible because the high level of the subject's amplified speech would cause acoustic feedback. That is, a high frequency squeal occurred when the amplified signal from the headphone was picked up by the ear-level microphone, re-amplified, and played back through the headphone. This problem was solved by placing the microphone in front of the subject's mouth instead of adjacent to the ear. This required an adjustment to be made in the headphone output to account for head diffraction effects, because the sound radiated from the mouth changes somewhat as it travels around a person's head to his/her own ear (Dunn & Farnsworth, 1939; Porschmann, 2000). This mouth-to-ear transfer function is gently sloping from the low to high frequencies, except for slight dips at 900 and 2700 Hz, and then drops off significantly above 6000 Hz. A final adjustment of the graphic equalizer was performed to simulate this effect.

3.2.2 Ear canal occlusion conditions

To study the influence of the occlusion effect, speech produced by a subject was recorded under three occlusion conditions, i.e., while his/her ear canals were occluded with three different hearing protectors. The maximum occlusion effect is known to be produced by occluding the ear canal right at the entrance. A hand-formed putty-type earplug (Mack's silicone putty earplugs) that does not extend into the ear canal was used for this condition. Minimum occlusion effects are known to be produced either by a deeply inserted earplug or by earmuffs with a large earcup volume. The first of these minimum occlusion conditions was tested using a fully inserted foam earplug (E·A·R® Classic®) and the second was assessed by using a set of earmuffs. The Sennheiser HDA 200 audiometric headphones that were used are actually Peltor H7 earmuffs (intended for protection from hazardous noise) with built-in earphone transducers. Thus, the Sennheiser HDA 200 headphones provided both the earmuff-induced occlusion effect also while acting as the headphones for the subject's voice feedback system.

The occlusion effect for each hearing protector fitting was quantified by measuring the sound level in each ear canal with and without the hearing protectors, while the subject vocalized the vowel /i/. IntriCon Tibbetts 151 Series sub-miniature microphones (0.10 inch diameter cylinder; 0.132 inches long) were used to simultaneously measure the level in both ear canals. These microphones were connected to a computer-based signal analysis system using a National Instruments 9234 compact data acquisition module (24-bit resolution; 51.2 kHz sampling rate).

The subject was instructed to watch the display on a hand-held sound level meter, and to sustain the vocalization at a comfortable level (e.g., 65 dB) for a few seconds until the measurement was made. The exact level was not important; however, it was critical for the subject to produce the same level when the vocalization was repeated when the protector was worn. The occlusion effect is represented by the difference (in decibels) between the level in the ear canal with and without the hearing protector in place.

3.2.3 Hearing protector attenuation conditions

Four attenuation conditions were evaluated: 0, 10, 20, and 30 dB. The 0 dB attenuation condition was used to evaluate the outcome solely due to the occlusion effect. This is an artificial listening situation that must be created where the subject is (in effect) not receiving attenuation from the particular hearing protectors being worn. Each of the four attenuation conditions was created by re-introducing the subject's own voice (at different levels) through the air-conduction restoration headphones worn in combination with the hearing protectors. Different amounts of attenuation were simulated by changing the headphone output. For example, the attenuation (insertion loss) provided by a 30 dB hearing protector would be completely offset by raising the headphone output by 30 dB.

3.2.3.1 Attenuation measurements

Figure 4 illustrates the test set-up for the hearing protector attenuation (insertion loss) measurements. For the two earplug test conditions, an IntriCon Tibbetts 151 Series sub-miniature microphone was positioned in each ear canal at a point that would be medial to the earplug when it was inserted, and temporarily held in place with adhesive tape. White noise was played at a level of 80 dBA through two stand-mounted loudspeakers located at 45-degree angles to the subject while the microphones measured the level in each ear canal, with the subject not wearing any earplugs.

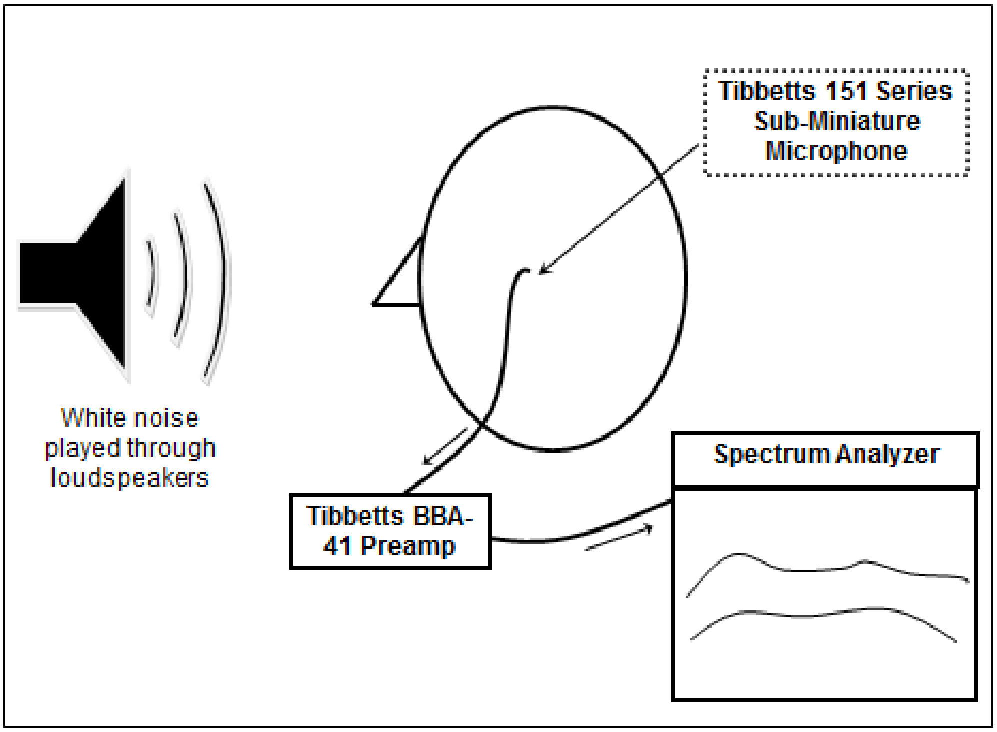

Figure 4. Instrumentation for hearing protector attenuation testing.

Next, earplugs were inserted into the subject's ear canals by the investigator. The microphone wires were inserted through the earplug, enabling the microphone to be located in the ear canal at the same position as in the previous step. For the disposable foam earplugs, a small hole was made through the center (without removing any of the foam material) to route the microphone wires. The expandable foam collapsed around the lower portion of the microphone where the wires attached and sealed the hole. The hand-formed putty-type earplugs were molded around the microphone wires when the ear canal was occluded at the entrance.

Finally, the white noise was raised to 90 dBA to ensure the level in the ear canal was above the noise floor of the microphones, and played again while the attenuated sound level in both ear canals was measured. The attenuation (insertion loss) of the earplug was determined by subtracting the occluded from the unoccluded measurement, minus the extra 10 dB.

Attenuation measurements of the earmuffs were made by a similar procedure as described above for the earplug condition. The microphone wires (29 AWG; 0.019-inch outside diameter) were thin enough to be routed under the headphone cushions without significantly interfering with the earcup seal.

As mentioned earlier in Section 2.5, the NRR is the manufacturer’s rating for the amount of sound attenuation provided by a hearing protector. Due to the known issues surrounding the NRR’s validity, it was used solely as a general guide for the amount of attenuation expected. Slight deviations from the labeled attenuation were anticipated and did not pose a problem for this study; however, the earplug was re-seated if the measured attenuation was substantially below the expected amount.

3.2.3.2 Setting the voice feedback system

After the attenuation measurements were obtained, overall amplification level and graphic equalizer adjustments were made to offset the attenuation of the earplugs. The occluded and unoccluded measurements were saved into a spreadsheet that was pre-configured to perform the necessary calculations. First, each one-third octave-band in the graphic equalizer was individually adjusted to make the frequency spectrum match the shape of the measured attenuation for each ear. Then the overall headphone amplifier gain level was used to set the correct level.

It is important to note that although none of the three hearing protectors exhibited uniform (flat) attenuation characteristics, the range of the lowest to the highest amount of attenuation for each one was less than 30 dB, which was the maximum range of the graphic equalizer (i.e., ±15 dB). The four attenuation level conditions (0, 10, 20, and 30 dB) were obtained by adjusting the master headphone output in 10-dB increments.

3.2.4 Background noise levels

Pink noise (i.e., constant energy per octave band; downward slope of 3 dB per octave) was used for this study, since it represents a well-defined spectrum and has a predominantly low frequency emphasis, which is typical of many industrial environments (Johnson & Nixon, 1974). A pink noise generator function on the Ashly NE4400 digital signal processor was internally routed to the subject's headphones through a signal mixer function within the same signal processor. Four different noise level conditions were used: quiet, 75, 85, and 95 dBA. The quiet condition was used to evaluate the occlusion effect in isolation. The 95 dBA level was chosen as the maximum since most industrial noise environments do not exceed this level, and unaided speech communication in higher ambient noise levels is usually impractical (Franks, 1988). All noise levels were calibrated and periodically confirmed by measurements conducted on the KEMAR manikin, and did not change throughout the course of the study.

3.2.5 Speech measurements

Several different options exist for choosing speech material for this experiment, each of which has certain benefits and drawbacks. Examples include: production of a sustained vowel sound;

repeating words or sentences from a list; reading an excerpt such as the commonly used Rainbow Passage; or simply providing a spontaneous speech sample. The overarching goal is to identify any speech differences found in real-life industrial working situations; however, this must be done within the context of a controlled experimental condition.

Instructing the subject to sustain a single phoneme/vowel sound for several seconds would create an ideal speech sample for subsequent acoustical analysis. Unfortunately, the subject cannot be expected to make such a vocalization understandable to a listener. Reciting a short passage would solve this problem, but only if all subjects had memorized it to avoid sounding like they were reading. Eliciting a spontaneous conversational speech sample would address both the understanding and natural-sounding issues, but this would introduce too much variability among the subjects' responses to be suitably analyzed.

Considering the above-mentioned constraints, short sentences/phrases developed as a speech test for industrial workplaces by Cluff et al. (1993) were chosen for this study. This test material comprises eight lists of phrases with twenty 3- to 5-syllable phrases in each set (see Appendix A). Most of the phrases are short commands, instructions, or questions. Each list was created to be phonetically balanced and of approximately equal difficulty. To enable direct comparison among the different experimental conditions, only one of the eight lists (List #1) was used in this study. To avoid differences caused by intonation, for this study four of the phrases (Nos. 1, 11, 14, and 20) were changed to be declarative rather than interrogative. This involved reversing the order of a few words and substituting two of the original words (see Appendix B).

The test materials spoken by each subject were recorded for later analysis. Recordings were obtained in a double-wall audiometric booth at the NIOSH Robert A. Taft laboratory building in Cincinnati, Ohio. A G.R.A.S. Sound & Vibration Type 40HF 1-inch low-noise measurement microphone system and a computer-based data acquisition system using a National Instruments 9234 compact data acquisition module (24-bit resolution; 51.2 kHz sampling rate) were used. The 1-inch microphone was connected to the manufacturer-recommended Type 26HF preamplifier and Type 12HF power supply. Together, this system has a measured sensitivity of 1,157 mV/Pa and a frequency response of ±2 dB from 10 Hz to 10 kHz. A G.R.A.S. Type 42AP pistonphone was used to record a calibration tone (250 Hz; 94 dB SPL) at the beginning of each WAV file, to enable precise scaling and subsequent analysis of the speech samples. All measurement instrumentation used in this study is sent to an accredited laboratory for annual calibrations.

Subjects were instructed to speak as if they were trying to be heard and understood by a person seated one meter away (i.e., at the measurement microphone location). A KEMAR manikin head/torso was positioned at the subjects' eye level behind the measurement microphone for this experiment. Subjects were told that the manikin represented an intended human listener.

The Cluff et al. (1993) phrases lend themselves to being recited in a way that closely resembles speech spoken in a noisy environment. To facilitate this, the phrases were projected sequentially onto a wall-mounted computer monitor located directly above the manikin's head. Subjects were prevented from simply "reading" the test materials by a MATLAB routine that controlled the display. Each phrase was shown on the computer screen for 1.5 seconds (in black colored block letters on a light gray background), and then the words were removed and a solid green color was shown for 2.5 seconds. The subjects were instructed to wait until the screen turned green before speaking. In order to maintain consistency across all measurement trials, the following instructions were read to the subject:

You will be wearing different hearing protectors and will be hearing different amounts of noise. Please watch for words to appear on the screen and say each phrase in such a way that your conversation partner (the manikin) will be able to understand what you said. Don't just read the words; wait until the screen turns green before speaking. There are 20 phrases, and it will take you about 80-90 seconds for the whole list. Don't worry if you make a mistake – just wait until the next phrase appears and keep going. After each set of 20 phrases, there will be a 10-15 second pause while I make a few adjustments, and then you will go right into the next list. There will be total of 16 lists before we need to change hearing protectors. Please let me know if you need a break or a drink of water before you are ready to continue.

3.3 STUDY PARTICIPANTS

3.3.1 Protection of human subjects

This study was non-exempt according to 45 CFR 46.110 (Department of Health and Human Services, 2005). The study protocol was submitted both to the University of Pittsburgh Human Subjects Review Board as well as the CDC/NIOSH Human Subjects Review Board for an expedited review. This study qualified for an expedited review because the proposed research methods presented no more than minimal risk to human subjects, and data collection was accomplished through noninvasive procedures that are routinely employed in clinical/research settings.

Study participants were paid volunteers recruited via personal contacts. Only individuals over 18 years old were eligible for participation in this study because the hearing protectors that were used are designed for working-age adults. No exclusions were made based on race/ethnicity, gender, or HIV status. Since participation in this study did not involve a risk of physical harm, women of childbearing potential were not queried as to pregnancy status nor tested for pregnancy. No other special subject populations (e.g., prisoners, mentally disabled persons) were enrolled in this study. Potential subjects were fully informed of the nature of the research project, the risks and potential benefits of study participation, and their rights as a research subject. A standard Informed Consent form was signed by the participant and the researcher prior to performing any screening/testing procedures.

All subject testing was conducted in an ambient environment of 95 dBA or less. Levels above 85 dBA are considered to be hazardous to unprotected ears; however, it is important to note that the hearing protectors worn during this study reduced the amount of noise exposure each subject received to a non-hazardous level. Even if a high noise level temporarily reached a subject's ears, the unprotected exposure time added up to significantly less than 48 minutes, which is the time required for a subject to receive a daily noise dose of 100% based on exposure to 95 dBA as computed according to the NIOSH recommended occupational noise exposure criteria (NIOSH, 1998). Using the NIOSH recommended criteria is more protective than the OSHA noise exposure regulation, which permits a 4-hour unprotected exposure to 95 dBA (OSHA, 1983).

3.3.2 Qualification procedures

Individuals eligible for participation in this study included only working-age adults (18 - 65 years old) who were able to successfully wear hearing protectors. Exclusion criteria included non-native speakers of English, the inability to read, and certain medical conditions that could invalidate the testing. Each subject's ear canals were examined with an otoscope; subjects were ineligible for participation in the study if there was excessive cerumen present, e.g., an amount that prohibited visualization of the eardrum and/or would interfere with ear canal microphone placement and earplug fitting. Potential participants were asked about the presence/absence of cognitive impairment, a motor speech disorder, or any related physical condition. While none of the subjects noted a positive history, participants would have been dismissed for any abnormal conditions.

To eliminate the potentially confounding effects a pre-existing hearing loss might have on speech production measures, subjects were required to have normal hearing sensitivity (i.e., hearing thresholds ≤20 dB HTL) at all audiometric test frequencies from 125 to 8000 Hz in each ear. An air-conduction pure-tone audiogram (using supra-aural earphones) was obtained on each participant. Testing was conducted in a double-wall sound-treated booth having ambient noise levels in accordance with ANSI S3.1-1999 (R2008), Table 1 (ears covered, supra-aural earphones) using an audiometer calibrated to ANSI S3.6-2010 specifications. Although this did not occur, if a subject were to volunteer for this study but be disqualified due to a pre-existing hearing loss, he/she would have been referred to his/her personal physician for follow-up. No medical diagnosis was offered by the researcher; only a description of the audiogram was provided.

3.4 TEST PROCEDURE

Subjects were seated in a double-wall audiometric booth facing the corner where the KEMAR manikin and computer monitor were located. The measurement microphone was located 1-meter away from the subject, directly in front of the manikin's mouth. The manikin, measurement microphone, and subject's head were located approximately on the same horizontal plane. To familiarize the subject with the test procedure and to establish a control condition, the subject was instructed to recite the first list of test phrases without wearing any earplugs/earmuffs (and no background noise). A second practice list was recorded with the subject wearing the HDA 200 headphones, without any voice feedback or background noise (the headphones were not plugged in for this test). The subject was then fitted with the first set of hearing protectors and the occlusion effect and insertion loss were measured according to the procedures outlined above.

For the actual testing, subjects were instructed to speak the test materials under the four attenuation conditions (0 dB, 10 dB, 20 dB, and 30 dB) and background noise levels (quiet, 75 dBA, 85 dBA, and 95 dBA) for that set of hearing protection. The pink background noise (along with the subject's voice) was delivered in real-time via the air-conduction restoration headphone system described above. Figure 5 depicts how the subjects and instrumentation were positioned for data collection. Note that the pink noise generator, graphic equalizer, and mixer are shown as three separate devices; however, the Ashly NE4400 signal processor actually performs all of these functions.

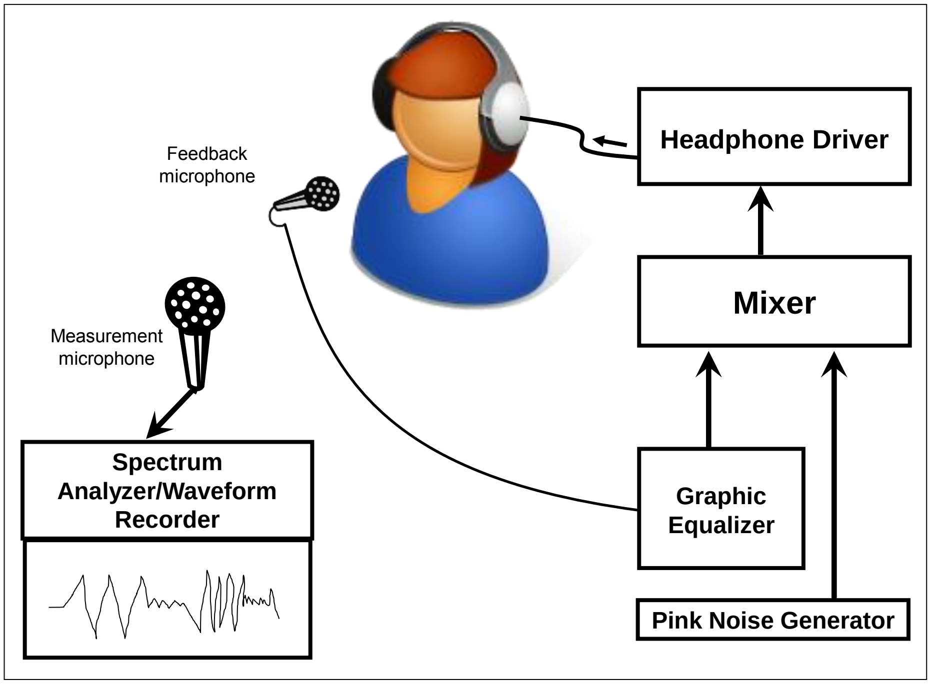

Figure 5. Instrumentation for data collection.

The same procedure was repeated for the other two hearing protectors (occlusion conditions). Testing for each occlusion condition took approximately one hour. Some subjects only completed one or two conditions on a particular day, while most of them stayed and completed all three hours of testing during one visit to the laboratory.

3.5 EXPERIMENTAL DESIGN

This study employed a split-plot design with complete blocks in which a subject represents a block. Dean and Voss (1999, p. 675) indicate that a split-plot design is useful when some factors are more inconvenient to change than others. In this study, the occlusion condition (i.e., continually removing/reinserting the earplugs) would be considerably more difficult to change than the other two factors. If the time slot of measurement is viewed as the experimental unit, the occlusion condition may be considered the whole plot and the split-plots are the 16 combinations of background noise and hearing protector attenuation. The order of occlusion conditions for each subject were randomized; however, after each occlusion condition (i.e., type of hearing protector) was set, all 16 combinations of hearing protector attenuation and background noise levels were run (in a randomized order) before changing the type of occlusion. Tables 6, 7, and 8 illustrate the matrices used for data collection. Appendix C contains the actual randomized subject testing schedule used.

Table 6. Data collection matrix for occlusion condition #1 (deep insertion foam earplug).

	Occlusion Condition: Deep insertion earplug (Minimum occlusion effect)															
	Background: quiet				Background: 75 dB				Background: 85 dB				Background: 95 dB			
	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB
S1																
S2																
S3																
S4																
S17																
S18																

Table 7. Data collection matrix for occlusion condition #2 (putty-type earplug).

	Occlusion Condition: At earcanal entrance (Putty-type HPD, Maximum occlusion effect)															
	Background: quiet				Background: 75 dB				Background: 85 dB				Background: 95 dB			
	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB
S1																
S2																
S3																
S4																
S17																
S18																

Table 8. Data collection matrix for occlusion condition #3 (earmuff).

	Occlusion Condition: Earmuff (Minimum occlusion effect)															
	Background: quiet				Background: 75 dB				Background: 85 dB				Background: 95 dB			
	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB
S1																
S2																
S3																
S4																
S17																
S18																

Depending on the covariance structure of the repeated measures, the intent was to analyze the data using a repeated-measures analysis of variance (ANOVA) and/or a linear mixed-model approach. The main purpose was to determine whether the occlusion condition or the attenuation condition affected the outcome variable. Additionally, the analysis tested for interaction effects.

A power analysis for a repeated-measures ANOVA was conducted using a standard deviation of 1.0 for the assumed means, a standard deviation of 5.0 for the error term, and a correlation between repeated measures (ρ) of 0.1. The term ρ is the value of the off-diagonal elements of the correlation matrix of repeated measures. The assumed covariance structure of the repeated measures was compound symmetry. Power was calculated with the software package PASS. Table 9 shows the sample sizes for the various factors and interaction terms obtained assuming $\alpha = 0.05$. Examination of this table indicates that a sample size of 18 was needed to obtain a power ($1-\beta$) of at least 0.90 for the three factors and all interactions.

Table 9. Statistical power calculations and projected sample size.

	Statistical Power Calculations and Projected Sample Size									
	N=2	N=4	N=6	N=8	N=10	N=12	N=14	N=16	N=18	N=20
Occlusion	0.1010	0.2458	0.3943	0.5303	0.6463	0.7402	0.8132	0.8682	0.9086	0.9375
Attenuation	0.1171	0.5756	0.8169	0.9297	0.9754	0.9920	0.9976	0.9993	0.9998	0.9999
Occ X Attn	0.0575	0.4110	0.6789	0.8457	0.9331	0.9733	0.9900	0.9965	0.9988	0.9996
Background	0.1171	0.5756	0.8169	0.9297	0.9754	0.9920	0.9976	0.9993	0.9998	0.9999
Occ X Bckg	0.0575	0.4110	0.6789	0.8457	0.9331	0.9733	0.9900	0.9965	0.9988	0.9996
Attn X Bckg	0.0396	0.3785	0.6322	0.8051	0.9060	0.9582	0.9826	0.9932	0.9975	0.9991

To guard against practice effects, each subject was familiarized with reciting the test materials under two practice conditions, as described earlier. Additionally, administration of the measurement trials was randomized to prevent sequencing effects. In line with the split plot design of the study, randomization of the occlusion condition was limited due to the impracticality of re-fitting the hearing protectors and re-measuring the attenuation numerous times on the same subject. Within each occlusion condition, the order of the 16 combinations of background noise and attenuation level, as well as the list of 20 phrases, were randomized.

Table 10 provides an analysis of the potential errors inherent in the study design. When multiple hypothesis tests are conducted, adjustments may be necessary to control the overall level of significance (to account for a potential inflated Type I error risk). The practical consequence of making a Type I error (i.e., finding a difference due to occlusion condition, hearing protector attenuation, or background noise level when no real difference exists) must be weighed against making a Type II error (i.e., reporting that there is no significant difference in speech production due to occlusion and/or attenuation conditions when such a difference actually exists). For this study, in order to balance the risk of incurring a Type I vs. Type II error, an α of 0.05 and β of 0.1 were selected.

Table 10. Analysis of the severity of potential research outcome errors.

Erroneous finding:	Consequence:	Error type:	Practical significance:	Severity of error:
Occlusion condition shows an effect	Recommend that noise-exposed workers wear HPDs that produce a certain occlusion effect	Type I	If the occlusion effect is small, the talker's voice is more natural-sounding	Low
			A large occlusion effect causes one's own voice to sound unnatural	High
Occlusion condition does not show an effect	No specific recommendations regarding the occlusion effect are given	Type II	Missed opportunity to recommend a method to increase speech level (by not recommending a particular occlusion effect)	High
Attenuation condition shows an effect	Recommend the HPD that provides a specified amount of attenuation for a particular noise environment	Type I	Although the HPD's attenuation is not affecting speech production, selecting the minimum necessary attenuation will prevent the feeling of isolation	Low
			If a high attenuation device is used, it could interfere with speech communication	High
Attenuation condition does not show an effect	No specific recommendations regarding HPD attenuation (at least for speech intelligibility) are given	Type II	Missed opportunity to recommend a method to increase speech level (by not recommending that the HPD with a certain amount of attenuation be selected)	High
Background noise level shows an effect	The Lombard Effect is already known. No specific recommendations can be given regarding HPD selection.	Type I	HPDs will be selected according to some criteria (other than speech intelligibility)	Low
Background noise level does not show an effect	No specific recommendations will be given regarding HPD selection	Type II	HPDs will be selected according to some criteria (other than speech intelligibility)	Low
There is an interaction between the occlusion and attenuation conditions	Recommend that both the occlusion effect and attenuation must be considered when selecting an HPD	Type I	Although both the occlusion effect and HPD attenuation are not affecting speech level, the particular combination of these two variables used could cause the talker's voice to be very unnatural sounding	High
There is no interaction between the occlusion and attenuation conditions	Recommend that only the main effect of occlusion or attenuation (if any) needs to be considered when selecting an HPD	Type II	Missed opportunity to recommend a method to increase speech intelligibility (by not recommending that both the occlusion effect and HPD attenuation be optimized)	High
There is an interaction between the occlusion condition and background noise level	Cannot change the background noise level; can only make a recommendation that a specific occlusion effect be obtained	Type I	If the occlusion effect is small, the talker's voice is more natural-sounding	Low
			A large occlusion effect causes one's own voice to sound unnatural	High
There is no interaction between the occlusion condition and background noise level	Recommend that only the main effect of occlusion (if there is one) needs to be considered when selecting an HPD (see above)	Type II	Missed opportunity to recommend a method to increase speech intelligibility (by not considering the interaction between the occlusion effect and background noise level)	High
There is an interaction between the attenuation condition and background noise level	Cannot change the background noise level; can only make recommendations regarding HPD attenuation (see above)	Type I	Although both the HPD attenuation and background noise level are not affecting speech production, minimizing the HPD attenuation is less likely to cause the feeling of isolation	Low
			If a high attenuation device is used, it could interfere with speech communication	High
There is no interaction between the attenuation condition and background noise level	Only the main effect of attenuation (if any) needs to be considered when selecting an HPD (see above)	Type II	Missed opportunity to recommend a method to increase speech intelligibility (by not considering the interaction between the HPD attenuation and background noise level)	High

4.0 RESULTS

4.1 PRELIMINARY MEASURES

4.1.1 Occlusion effect measurements

The occlusion effect produced by each hearing protector was obtained by measuring the sound level in each ear canal while the subject vocalized the vowel /i/ first without the hearing protector and again with the protectors in place. As described earlier, Figure 2 provides an example of these measurements. A value for the occlusion effect in each ear was obtained by subtracting the level measured with the hearing protectors being worn from the level measured without any hearing protectors.

Figure 6 contains the average values of the occlusion effect for each of the three occlusion conditions (as produced by the three different hearing protectors) for all 18 subjects. As expected, the occlusion effect occurred at 2000 Hz and below, and the largest occlusion effect was seen with the putty-type earplugs because they block the ear canal right at the entrance. The earmuffs produced the least occlusion effect, while the effect of the foam earplugs was between the other two occlusion conditions. These results follow the occlusion effect patterns found by other researchers (e.g., Stenfelt & Reinfeldt, 2007).

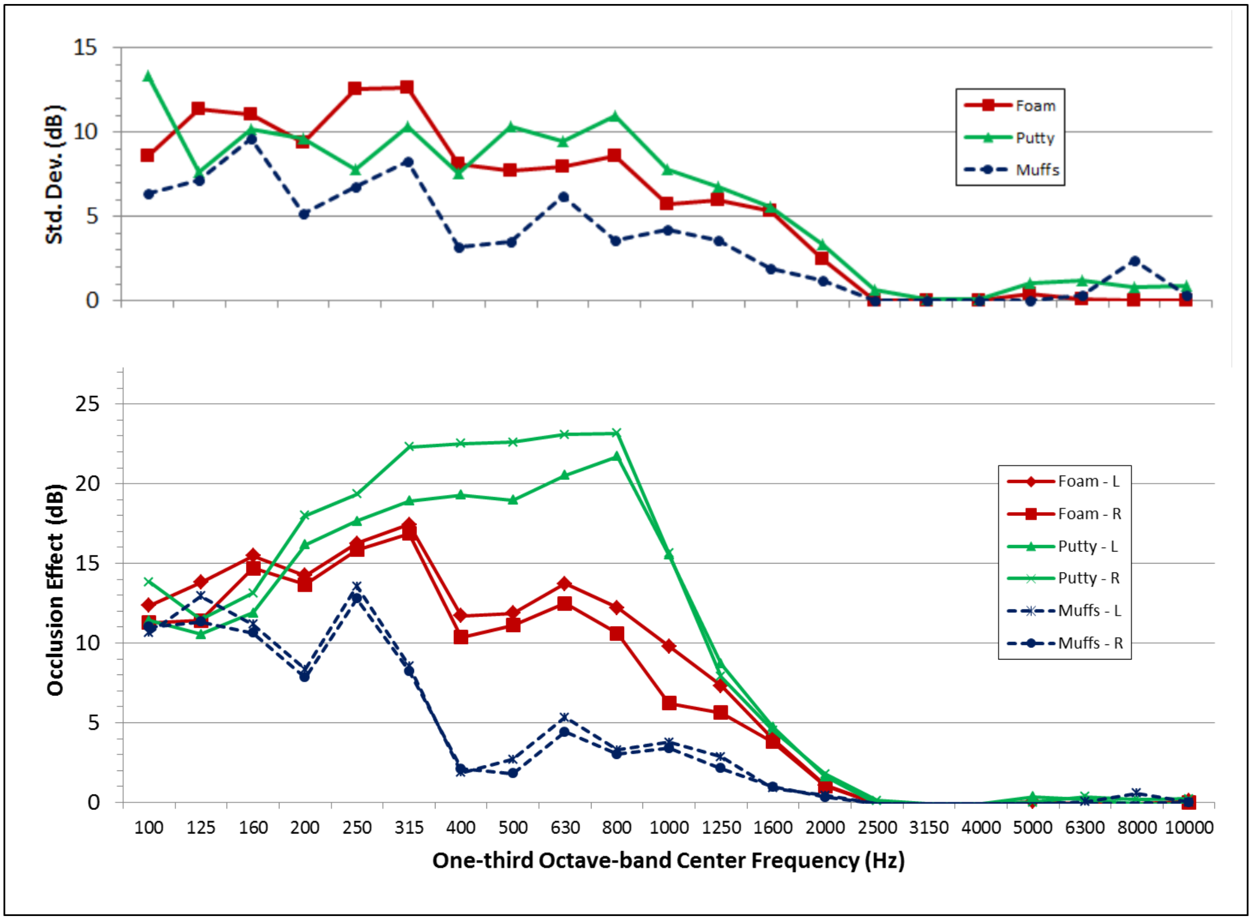

Figure 6. Average measured occlusion effect for each occlusion condition (hearing protector type). Standard deviations are for average of both ears for each hearing protector type.

4.1.2 Hearing protector attenuation measurements

A microphone-in-real-ear technique was used to measure the attenuation of each hearing protector on both ears of each subject. The graph in Figure 7 depicts the average attenuation results across all 18 subjects for each of the three hearing protectors. As expected, all three protectors provided the most attenuation at the higher frequencies and the least attenuation at the lower frequencies. The foam earplugs attained the highest attenuation; the earmuffs provided somewhat less attenuation than the foam earplugs; and the putty-type plugs provided the least amount. Comparisons were made between the measured attenuation at each one-third octave-band from 125 Hz to 8000 Hz and the manufacturers' reported data. Average attenuation results were less than the manufacturer's labeled values as well as the overall NRR reported for each protector, which was not unexpected. The manufacturer's attenuation data were used only as a rough guide when fitting each individual subject with the earplugs. For the purposes of this study, it was not necessary to achieve the labeled NRR value; the exact amount of attenuation provided by each protector just had to be known in order for it to be offset by the voice feedback system.

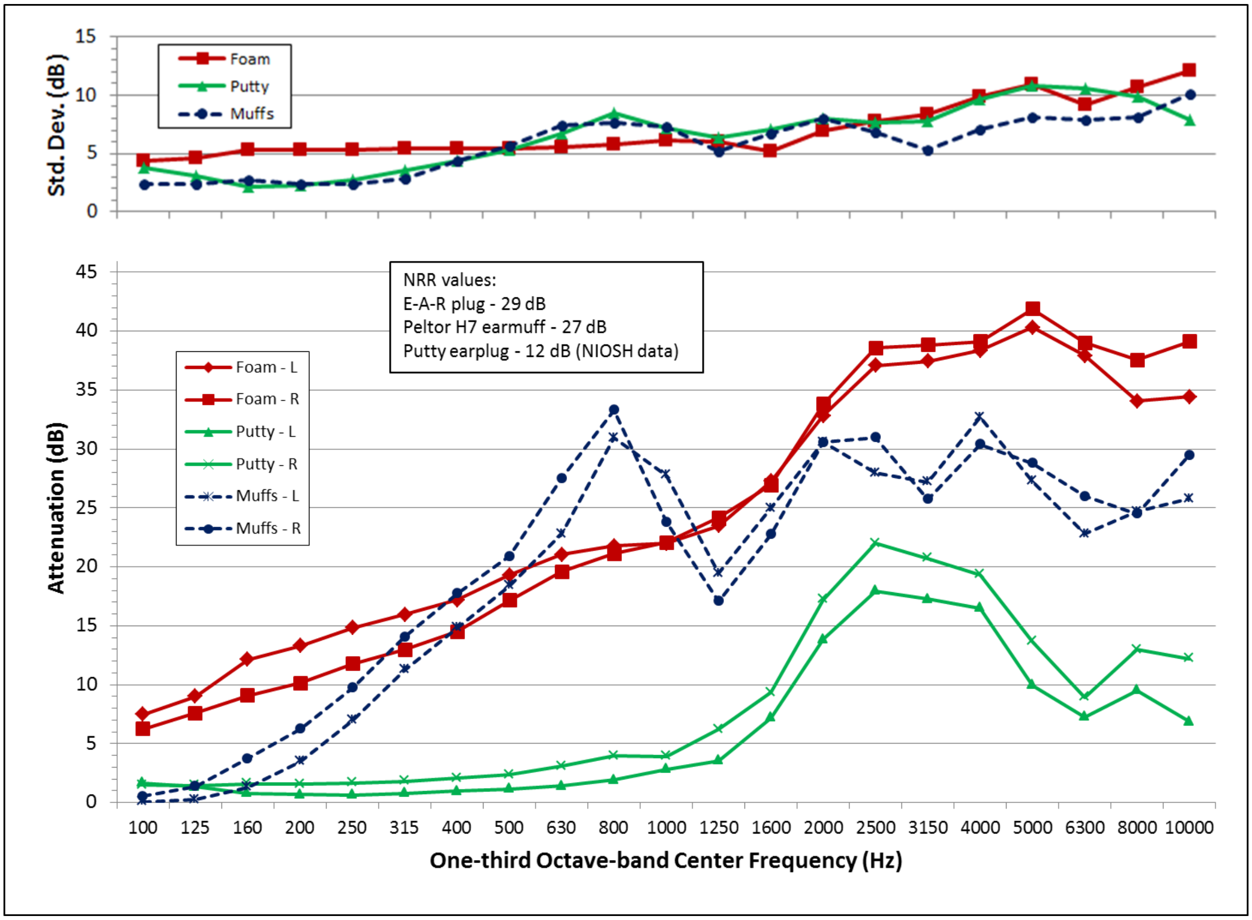

Figure 7. Average measured attenuation (mean values) for each hearing protector. Standard deviations are for average of both ears for each hearing protector type.

4.2 EFFECT OF OCCLUSION TYPE, ATTENUATION, AND NOISE

The specific aims of this research included two questions: 1.) What is the effect on voice output level when the attenuation provided by a hearing protective device worn by an individual is carefully controlled? and 2.) If changes in speech production are observed when hearing protection is worn, which mechanism – ear canal occlusion or hearing protection attenuation – has a greater effect on an individual's voice output level? The purpose of the analysis was to determine the effects of occlusion, attenuation, and noise level on the voice level of the speaker in order to address these questions.

4.2.1 WAV file analysis

Four of the twenty phrases (Appendix B) were chosen for analysis: "Block the door," "Fill this out," "Block the road," and "Crack the lid." These phrases were selected primarily for their consistency in pronunciation across the 16 test conditions for each subject. One reason for not selecting certain phrases for analysis was that subjects tended to emphasize different syllables depending on what the preceding phrase was, seemingly in an attempt to connect the individual phrases together in a conversational manner. Thus, there were noticeable differences in the way a particular phrase was spoken depending on the phrase that came immediately before it. Likewise, despite being randomized, phrases that appeared often at the beginning of a list were not included in the analysis because they were obviously spoken either softer or louder than the remainder of the list, apparently as a carry-over from the noise/attenuation condition that had just been completed.

A WAV file analyzer software program (Nelson Acoustic Software) was used to post-process the audio recordings. Using an on-screen level vs. time plot, the start/stop times of each utterance were able to be accurately identified. One-third octave-band sound pressure levels obtained at each 5-msec time interval were summed to provide the overall sound pressure level of each individual phrase.

A priori, one might wonder if the voice output levels would cover a large enough range to suggest that differences might be meaningful between the conditions examined in this experiment. In order to view the range of voice output levels measured in this experiment, boxplots of all the responses for each subject for all occlusion, attenuation, and noise conditions are shown in Figure 8. For each subject, the boxplot represents 192 data points, with the minor exception of three subjects who had missing data (i.e., failed to respond) for one of the test conditions. The range of voice level was quite pronounced for some subjects (e.g., subjects 3 and 11) and not for others (e.g., subjects 12 and 14). It appears that at least for many subjects a meaningful difference in voice output levels may be achieved under the varying conditions included in this experiment.

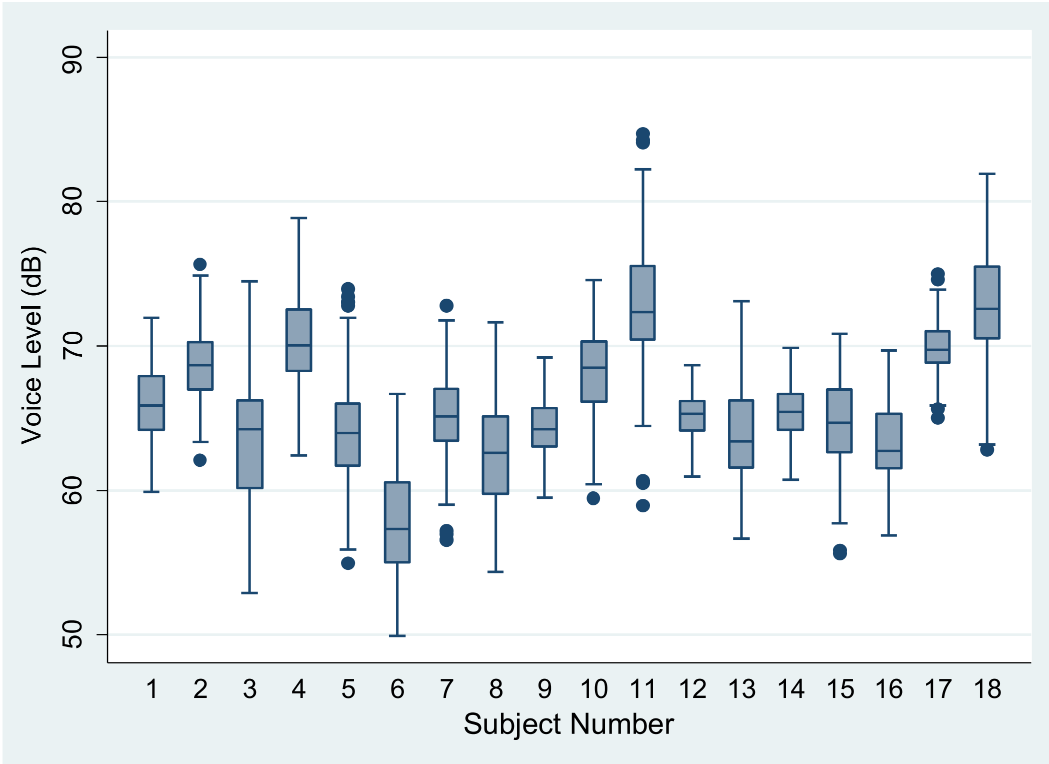

Figure 8. Range of voice levels for all experimental conditions for all subjects.

4.2.2 Linear mixed model

A linear mixed model (Fitzmaurice, Laird, & Ware, 2011) was developed that used voice level as the outcome variable and occlusion, attenuation, noise, age, phrase, and gender as explanatory variables. Age, phrase number, and gender were included primarily as nuisance variables, as they were taken into account but are not of direct interest in this study.

As described in section 3.5, the design of the experiment was that of a modified split-plot. The whole plot experiment unit was the occlusion type (i.e., foam, putty, or earmuff). The subplot experimental unit was the combination of noise level and attenuation level. In other words, the 16 possible combinations of noise level (0, 75, 85, or 95 dBA) and attenuation level (0, 10, 20, and 30 dB) were applied in random order for any given level of occlusion. The subject was treated as a random effect, as was the effect of occlusion. Thus, the overall linear mixed model for the analysis was:

$$y_{ijklmn} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \xi_l + s_{ln} + a_{iln} + \phi_m + \theta x + e_{ijklmn}$$

where y_{ijklmn} = voice level of talker, n = 1, 2, 3,…, 17, 18

μ = overall mean

α_i = fixed effect of occlusion type, i = 1, 2, 3 [foam, putty, earmuff]

β_j = fixed effect of noise, j = 1, 2, 3, 4 [0, 75, 85, 95 dBA]

γ_k = fixed effect of attenuation, k = 1, 2, 3, 4 [0, 10, 20, 30 dB]

$(\alpha\beta)_{ij}$ = fixed effect of interaction of occlusion type and noise

$(\alpha\gamma)_{ik}$ = fixed effect of interaction of occlusion type and attenuation

$(\beta\gamma)_{jk}$ = fixed effect of interaction of noise and attenuation

$(\alpha\beta\gamma)_{ijk}$ = fixed effect of interaction of occlusion type, noise, and attenuation

ξ_l = fixed effect of gender, i = 1, 2 [male, female]

ϕ_m = fixed effect of phrase, m = 1, 2, 3, 4 [four phrases used in the analysis]

θ = regression parameter characterizing effect of age (x)

s_{ln} = random effect of subject with $s_{ln} \sim N(0, \sigma_s^2)$

a_{iln} = random effect of occlusion type with $a_{iln} \sim N(0, \sigma_a^2)$

e_{ijklmn} = random error with $e_{ijklmn} \sim N(0, \sigma_e^2)$

The results of fitting the above model to the data are shown in Table 11. All of the fixed effects of interest (occlusion, noise, and attenuation) had significant effects, as did their interactions. Appendix D contains the marginal means, which are referred to as least squares means as calculated in Statistical Analysis System (SAS Institute, Inc.) software, as well as model diagnostics (using measured voice level as the outcome variable). In addition, "slice" tests are included. These are tests that show – for one variable – for which levels of another variable there is a significant difference.

Table 11. Tests of fixed effects with voice level as the outcome variable.

Effect	Numerator Degrees of Freedom	Denominator Degrees of Freedom	F Value	Pr > F
Occlusion type	2	35	4.23	0.0227
Noise	3	3343	1131.35	<.0001
Occlusion type × Noise	6	3343	78.71	<.0001
Attenuation	3	3343	292.58	<.0001
Attenuation × Occlusion type	6	3343	6.84	<.0001
Attenuation × Noise	9	3343	3.06	0.0012
Attenuation × Occlusion × Noise	18	3343	1.91	0.0114

4.2.3 Occlusion type

Table 12 contains the summary statistics by occlusion type, as defined by which hearing protector was being worn. Of the three occlusion conditions evaluated, the foam earplug occluded the ear closest to the tympanic membrane, while the earmuff occluded the ear external to the head (surrounding the pinna). The putty earplug occluded the ear canal midway between, at the entrance to the ear canal. The baseline results in the first row of Table 12 were from measurements of the control condition, where no earplugs or earmuffs were worn, and no background noise was present. In the following rows, the means of all voice level measurements for each of the three occlusion types are shown. For each occlusion type there are 18 values – each calculated from 64 data points (4 attenuation levels × 4 noise levels × 4 phrases). Based on the linear mixed model results in Table 11 ($F = 4.23$, $p = 0.0227$), the evidence is to reject the null hypothesis that the effects due to the three occlusion types are all equal.

Table 12. Summary statistics for voice output (in dB) by occlusion type.

Occlusion Type	N	Mean	Standard Deviation	Median	Lower quartile	Upper quartile	Maximum	Minimum
Baseline	18	61.8290	3.51643	62.2075	60.0614	64.3344	69.7178	54.4843
Foam	18	65.5841	4.11046	65.4444	62.8273	67.8016	72.4935	55.8348
Putty	18	67.0476	4.08439	65.8786	65.0842	69.0090	76.4774	60.9513
Earmuffs	18	65.8661	4.14042	65.6652	63.6883	69.5147	72.3714	57.2228

The data set consisting of the 18 values of mean voice level for each occlusion type was then used to calculate the means and 95% confidence intervals $\left(\bar{x} \pm t_{(0.975,\,17)} \, {}^{s}\!/\!_{\sqrt{n}} \right)$ for different occlusion types. Figure 9 illustrates the effect of occlusion type on voice level for different noise levels. Each mean is based on measurements taken for the 16 combinations of phrase and attenuation level (4 × 4). Follow-up testing revealed that some of the pairwise comparisons between the Foam and Putty earplug conditions and the Earmuff and Putty earplug condition achieved significance, while the Foam earplug and Earmuff conditions were not statistically different. Specifically, none of the comparisons were significant in the quiet or 75 dBA noise condition, while significant differences appeared when the noise level was 85 and 95 dBA. Appendix E contains a table of these results. With such a large number of comparisons the Tukey-Kramer adjustment was used to maintain an overall significance level of 0.05.

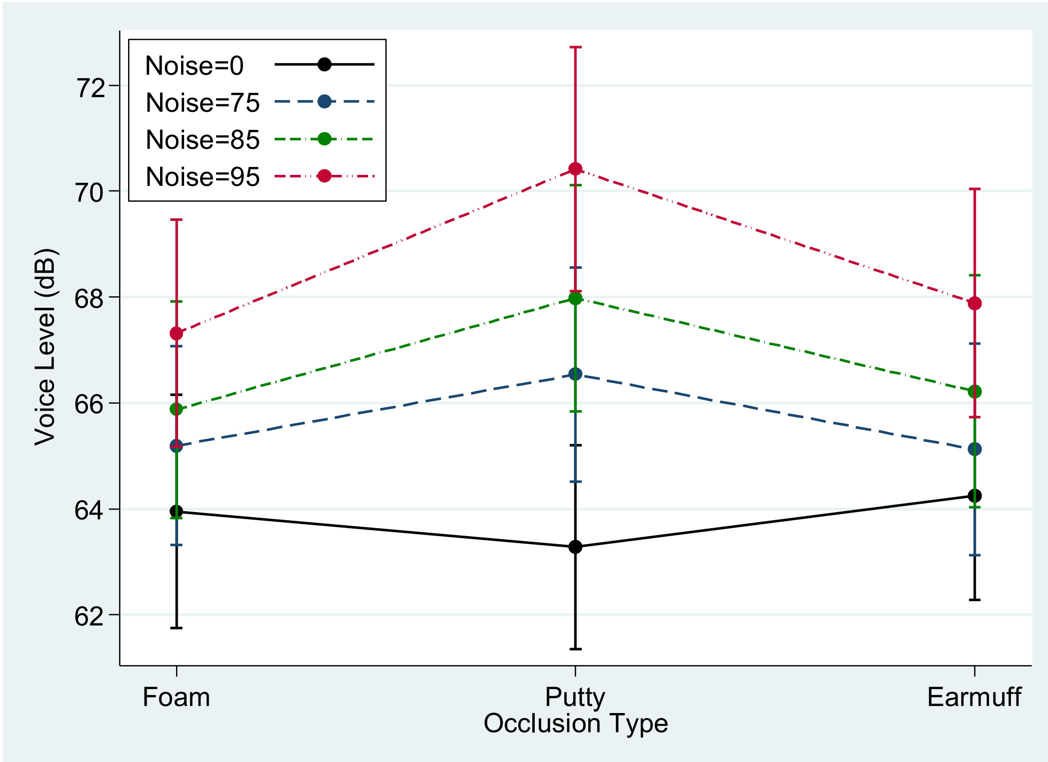

Figure 9. Arithmetic means and 95% confidence intervals of voice level for different occlusion types and noise levels.

4.2.4 Attenuation level

The summary statistics for the four attenuation conditions are shown in Table 13. To look at the effect of attenuation alone, the mean for each subject and attenuation level was calculated. Each mean was based on 48 data points (except in the case of missing data), covering all combinations of occlusion type, noise level, and phrase (3 × 4 × 4). The 18 means (one for each subject) for each attenuation level were then used to calculate the summary statistics shown in Table 13. The linear mixed model results in Table 11 ($F = 292.58$, $p < 0.0001$) provide evidence against the hypothesis of equal effects with different attenuation levels.

Table 13. Summary statistics for voice output (in dB) by attenuation level.

Attenuation	N	Mean	Standard Deviation	Median	Lower quartile	Upper quartile	Maximum	Minimum
0 dB	18	64.7515	4.05355	64.6313	62.2874	67.9124	72.6002	56.5702
10 dB	18	66.1471	3.94139	65.5787	63.4898	68.6660	73.4947	58.2396
20 dB	18	66.7761	3.96621	65.4075	64.7176	69.8965	74.0758	58.3734
30 dB	18	66.9828	3.77871	65.7495	65.1103	69.9824	74.0120	58.8287

The mean values of voice level and corresponding 95% confidence intervals over the range of attenuation conditions for the four different noise levels are shown in Figure 10. The mean voice level for each subject for each combination of attenuation and noise level was based on 12 data points (from all combinations of the three occlusion types and the four phrases) and are presented in this graph.

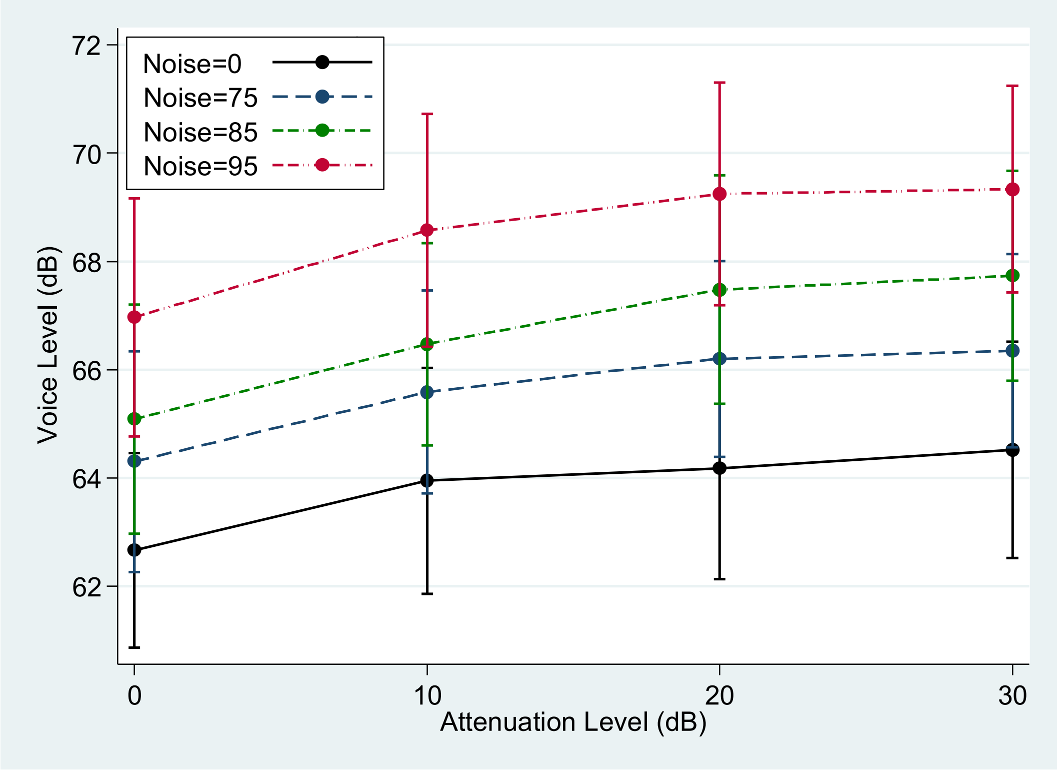

Figure 10. Arithmetic means and 95% confidence intervals of voice level for different attenuation conditions and noise levels.

Pairwise comparisons for the different attenuation amounts and noise levels are contained in Appendix F. For all noise levels the increase in voice level is highly significant as the attenuation increased from 0 to 10 dB. The voice level also increased significantly as attenuation increased from 10 to 20 dB for all noise levels except the quiet (0 dBA) condition. Conversely, the voice level did not increase significantly as the amount of attenuation increased from 20 to 30 dB for any of the noise levels.

4.2.5 Interaction effects

Table 14 contains the marginal means for the different combinations of occlusion types and attenuation levels.

Table 14. Marginal means for occlusion type and attenuation level.

Attenuation	Occlusion	Estimate	Standard Error	DF	t Value	Pr > |t|
30 dB	Earmuffs	66.9862	0.8521	3343	78.61	<.0001
30 dB	Putty	67.7201	0.8521	3343	79.48	<.0001
30 dB	Foam	66.2468	0.8521	3343	77.75	<.0001
20 dB	Earmuffs	66.6185	0.8521	3343	78.19	<.0001
20 dB	Putty	67.4895	0.8521	3343	79.21	<.0001
20 dB	Foam	66.2210	0.8521	3343	77.72	<.0001
10 dB	Earmuffs	65.7456	0.8523	3343	77.14	<.0001
10 dB	Putty	67.1868	0.8521	3343	78.85	<.0001
10 dB	Foam	65.4936	0.8521	3343	76.86	<.0001
0 dB	Earmuffs	64.0962	0.8521	3343	75.23	<.0001
0 dB	Putty	65.8051	0.8521	3343	77.23	<.0001
0 dB	Foam	64.3761	0.8521	3343	75.55	<.0001

The results may be graphed as a function of occlusion type for different attenuation levels (Figure 11) or as a function of attenuation level for different occlusion type (Figure 12). All

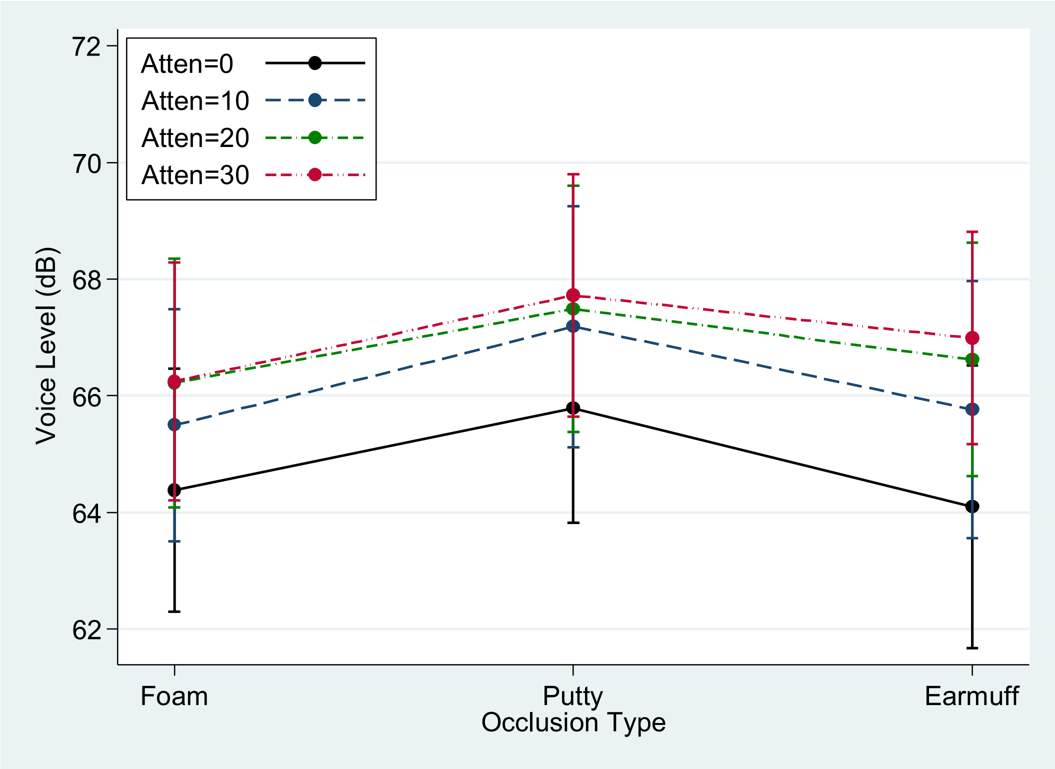

Figure 11. Arithmetic means and 95% confidence intervals of voice level as a function of occlusion type for different attenuation levels.

possible pairwise comparisons pertaining to both Figures 11 and 12 are presented in Appendix G. The Tukey-Kramer adjusted p-values are the ones of primary interest, as they preserve an overall alpha of 0.05. All pairwise comparisons within the same attenuation level in Figure 11 were non-significant. In Figure 12, all comparisons were significant as the attenuation level increased from 0 dB to 10 dB. As the attenuation level increased from 10 dB to 20 dB, the differences in the measured voice level for the foam earplug and earmuff occlusion conditions were significant while the putty earplug occlusion condition was not significant. None of the differences were significant between the 20 dB and 30 dB attenuation levels.

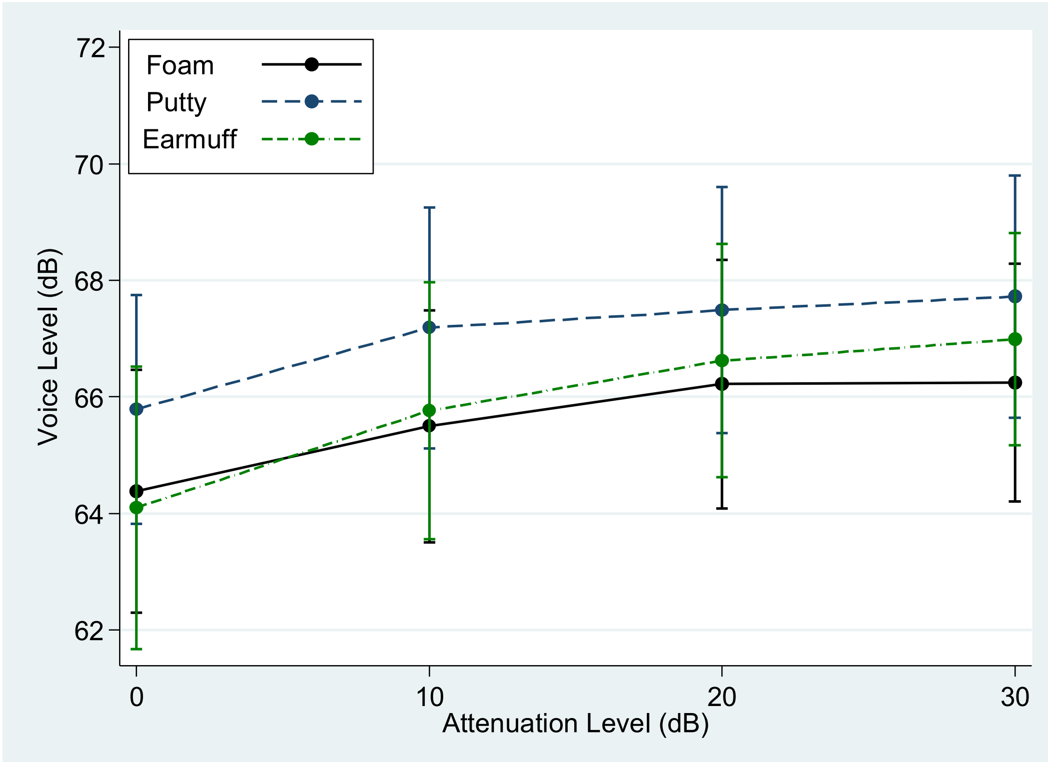

Figure 12. Arithmetic means and 95% confidence intervals of voice level as a function of attenuation level for different occlusion types.

Interaction effects were further explored by simultaneously graphing all three variables of interest: occlusion type, amount of attenuation, and noise level. Voice output levels as a function of occlusion site, as broken down by noise level are shown in Figure 13. This graph expands upon the information presented in Figure 9. The foam earplug created the deep canal occlusion condition, the putty earplug occluded the ear canal at the entrance, and the earmuff effectively occluded the ear externally around the pinna. The trend reversal between the quiet condition (bottom curve in each pane) and all three background noise conditions (upper three curves in each pane) illustrates how the occlusion site differentially affects the voice level, depending on whether or not background noise is present.

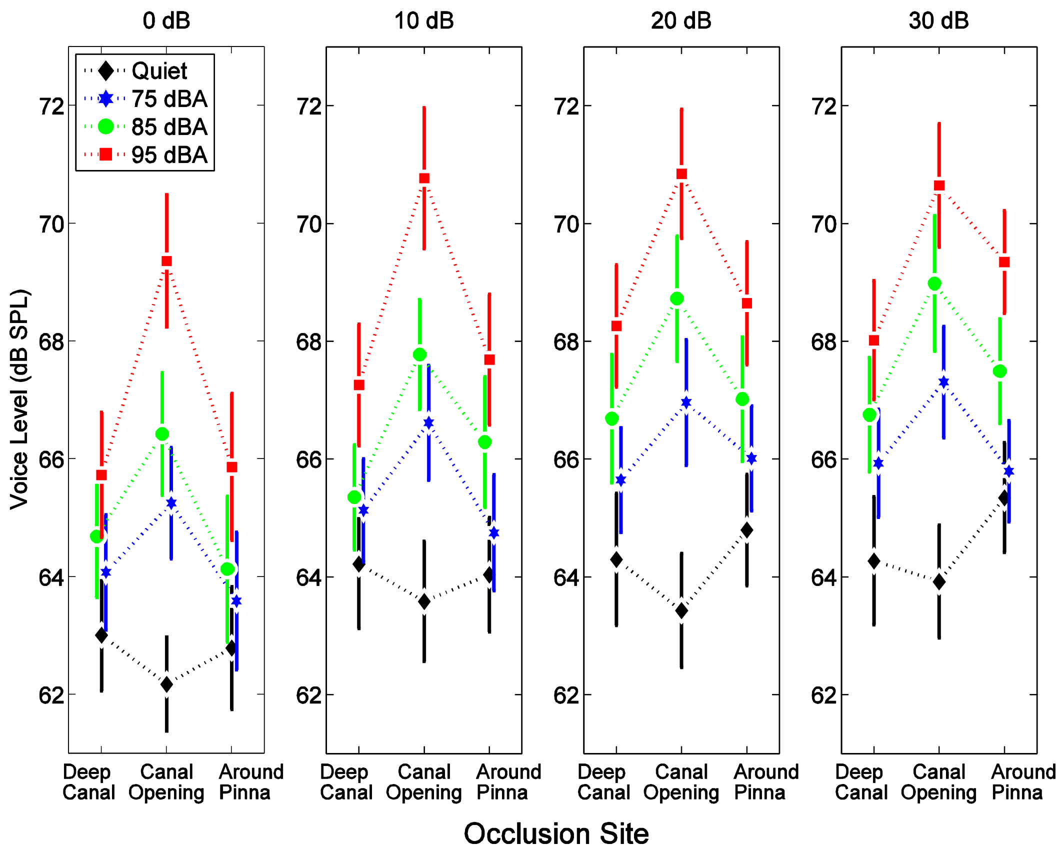

Figure 13. Arithmetic means of voice output level as a function of occlusion site for different attenuation and noise levels (error bars = standard error of the mean).

Voice output levels as a function of attenuation level, broken down by each background noise condition, are shown in Figure 14. This graph expands upon the information presented in Figure 10 by illustrating how attenuation provided by the hearing protector has a different effect depending on the occlusion condition. While voice output increases with increasing attenuation for all hearing protector types, the increase is substantially greater with the largest occlusion effect produced by putty earplug, which sealed the ear canal at the entrance.

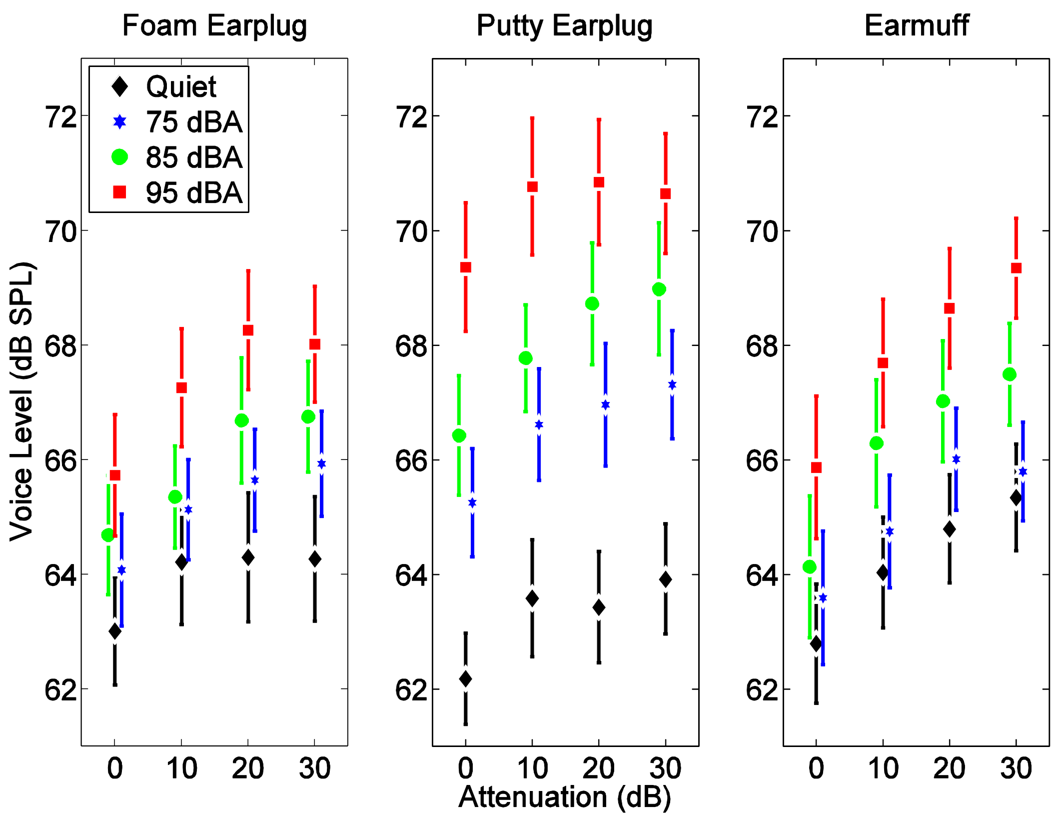

Figure 14. Arithmetic means of voice output level as a function of attenuation level for different occlusion types and noise levels (error bars = standard error of the mean).

5.0 DISCUSSION

5.1 EFFECT OF OCCLUSION TYPE, ATTENUATION, AND NOISE

This investigation had two specific aims. The first was to determine the effect on voice output level when the attenuation provided by a hearing protective device worn by an individual was carefully controlled. If changes in vocal output are observed when hearing protection is worn, the second goal was to determine which mechanism – ear canal occlusion or hearing protector attenuation – has a greater effect on an individual's speech output. The data suggest that the answers to these questions are dependent on the level of background noise, with the pattern of results being different for the quiet condition as compared to all three noise conditions. There is evidence to suggest that changes in a person's voice output levels when hearing protectors are worn and background noise is present are due to how the ear canal is occluded. Additionally, changes in a person's voice levels when hearing protectors are worn and background noise is present are affected by the attenuation provided by a hearing protector. Therefore, both of the null hypotheses stated in Section 3.1.1 were rejected.

Figures 9 and 13 show that the occlusion effect acted as would be expected in the quiet condition (Kryter, 1946; Zwislocki, 1953; Berger & Kerivan, 1983). Without being exposed to any background noise, voice levels were lower when the subjects wore the putty earplugs (i.e., when the occlusion effect was greatest) as compared to the other two types of hearing protectors.

This would be predicted by the increase in self-perceived voice level induced by occluding the ear canal right at the entrance. Measured voice levels were lowest when the hearing protector attenuation was experimentally removed (i.e., the 0 dB attenuation condition), although the speech levels only increased 1-2 dB for any of the three levels of attenuation.

Interestingly, the occlusion effect caused the exact opposite effect when any amount of background noise was added. In the three levels of noise (75, 85, and 95 dBA) that were tested, occluding the ear canal at the entrance with the putty plug (largest occlusion effect) caused the talker to raise his/her voice level substantially more than it was raised when the occlusion occurred deeper inside the ear canal (in the case of the foam earplug) or farther out (when the earmuff was worn) which are both conditions of least occlusion effect. This effect was observed regardless of the amount of attenuation the hearing protector was providing. Similar to what was found in the quiet condition, all three noise conditions caused the measured voice level to increase slightly from the 0 dB to 10 dB attenuation conditions; however increasing the amount of attenuation from 10 dB to 30 dB did not significantly increase vocal output.

Mentioned earlier as one of the reasons for conducting this study, an adequate description for the combination of the occlusion effect and the Lombard effect for talkers wearing hearing protection has not been published in the literature. For example, Kryter (1946) and Casali et al. (1987) reported that talkers raised the level of their voices by approximately 4 dB when they wore hearing protection in quiet, while Navarro (1996) and Tufts and Frank (2003) reported slight decreases in voice level in the same condition. All previous attempts to explain this discrepancy presumed that differences in the magnitude of either the occlusion effect and/or the hearing protector attenuation were the underlying cause(s). A comprehensive understanding was not previously possible because the underlying quantities were unknown (i.e., not measured or not reported in earlier research). In the case of little or no difference between occluded and unoccluded speech levels in quiet, Tufts and Frank (2003) speculated that shallow insertion of the earplugs provided an acoustic seal, although such incomplete insertion caused the attenuation of the air-conduction component and enhancement of the bone-conduction component of the subjects' speech to offset each other. The results of the present study provides evidence to show how this is a plausible explanation. For any given level of hearing protector attenuation, a talker's voice output level will change depending on the ear canal occlusion site, which can be manipulated by altering the earplug insertion depth.

Based on the findings in this study, the question of which mechanism has a greater influence on vocal output – the occlusion effect or the hearing protector attenuation – can only be accurately answered by knowing the ambient noise level. Increasing the noise level always caused an increase in voice level. Furthermore, increasing the noise level also causes the primary influencing factor to switch from the hearing protector's attenuation to the occlusion effect. This is illustrated in Table 15, which shows the differences in voice level as produced by the different occlusion and attenuation conditions for each of the four noise levels, which were computed from the values plotted in Figures 13 and 14.

Table 15. Average differences in voice output level between the minimum occlusion effect conditions (foam earplug and earmuff) and the maximum occlusion effect condition (putty earplug).

	Occlusion effect only (0 dB attenuation)	10 dB atten.	20 dB atten.	30 dB atten.
Quiet	-0.72 dB	1.23 dB	1.65 dB	1.91 dB
75 dBA noise	1.42 dB	1.11 dB	1.99 dB	2.03 dB
85 dBA noise	2.02 dB	1.41 dB	2.45 dB	2.71 dB
95 dBA noise	3.56 dB	1.68 dB	2.65 dB	2.88 dB

The quiet condition is contained in the first row of Table 15, where it can be seen that the change produced by any amount of attenuation was greater than the change produced solely by the occlusion effect. In the 75 dBA and 85 dBA noise conditions, the occlusion effect made a larger difference than 10 dB of attenuation did, while 20 dB and 30 dB of attenuation produced greater changes than brought about by the occlusion effect. In the 95 dBA noise condition, the occlusion effect alone was the dominant factor. Thus, the characteristic of a hearing protector that is more likely to cause the wearer to raise his/her voice level may be predicted for any set of occlusion and attenuation conditions; however, it will change depending on the noise level in which the protector will be used.

5.2 PRACTICAL IMPLICATIONS

When examining the results of this study and comparing the findings to previous research, it is important to point out that many of the comparisons between speech levels when wearing/not wearing hearing protectors reported in other studies were performed in unrealistic situations. Most notably, many of the earliest studies subjected their participants to unprotected sound levels that are known to be hazardous. Obviously, much larger differences would have been found in the present study if one of the conditions was for the subjects to NOT wear hearing protectors. Predictably, the Lombard effect would have been more pronounced, but nobody should be exposed to high noise levels without wearing hearing protection, so it would not have any practical applicability.

Howell and Martin (1975) found that listeners' average intelligibility scores decreased by as much as 25% when talkers wore hearing protection. Hormann, Lazarus-Mainka, Schubeius, and Lazarus (1984) reported that speech intelligibility results indicated significantly less was understood when both talkers and listeners were wearing earplugs. Unfortunately, as Casali, Horylev, and Grenell (1987) concluded, individuals would have to make a conscious and unnatural effort to speak loud enough to be understood in high background noise levels. A possible solution to this dilemma that has not been previously suggested is to select a particular type/style of hearing protector with appropriate attenuation characteristics that would subconsciously enhance a talker's voice level. Raising one's voice level will increase the signal-to-noise ratio for the listener, thereby increasing the chances of correctly hearing and understanding the spoken message.

The findings in the present study suggest that choosing hearing protectors to maximize the occlusion effect will aid verbal communication in a noisy environment. This is because a large occlusion effect was shown to significantly increase a person's voice level in background noise. An important caveat is that the distinct change in self-perceived voice quality induced by the occlusion effect is often found to be objectionable by hearing protection users, and must be acknowledged and appropriately managed. A simple way to alleviate this issue would be to have the individual don the hearing protector in the presence of background noise, because talking in a quiet environment while wearing hearing protection accentuates the resulting low frequency or resonant quality of one's own voice. Otherwise, the wearer may want to choose a different type/style of hearing protector with a smaller occlusion effect, which should be discouraged when optimal speech communication is desired.

Attenuation provided by the hearing protector also increases the talker's voice level, with the first 10 dB of attenuation having the most effect. Increasing the attenuation beyond 20 dB did not cause any additional increase in voice output level. Therefore, a hearing protector that provides the minimum amount of attenuation necessary for the particular noise environment should always be selected. Fortunately, 10 dB of attenuation generally is sufficient to reduce exposures to a safe level of 85 dBA because the vast majority of industrial noise environments do not exceed 95 dBA (Franks, 1988). Another advantage for wanting the lowest possible attenuation is that it avoids the problems created by overprotection, such as feelings of isolation when too much of the environmental sounds are removed (European Committee for Standardization, 2004).

Although the largest occlusion effect in this study was attained by using a putty-type earplug, as mentioned previously, a partially inserted foam earplug could also induce a large occlusion effect. Therefore, as long as a person receives enough attenuation from a foam earplug, a less-than-full insertion depth may actually be desirable. This is obviously counterintuitive to common thinking about insert-type earplugs, yet may be recommended based on what is now known about the interaction of the occlusion effect, earplug attenuation, and ambient noise level. One remaining unknown is whether the annoyance caused by the occlusion effect in quiet also holds true when the talker is in a noisy environment. If subsequent research determines that the change in one's self-perceived voice does not bother an individual when he/she is wearing earplugs and is talking in a high noise area, then it would be beneficial to increase the occlusion effect for all hearing protector types.

5.3 LIMITATIONS OF THE STUDY

The primary strength of this study is that it was the first experiment to simultaneously examine the effects of hearing protector attenuation and occlusion effect on voice output level, in several background noise conditions. The data are subject to at least two limitations, however. First, due to the increased time commitment that would be required for each subject, only one type of test material (3-5 syllable phrases) was used in this study. The effect of other types of test materials and/or spontaneous (i.e., unscripted) conversation was not evaluated. Similarly, the effects of talker motivation/intent or visual/verbal feedback from a conversation partner were not addressed in this study. These are all elements of normal conversation that could influence a talker's voice level.

Second, none of the more advanced types of hearing protectors, such as flat or uniformly attenuating devices with a moderate amount of attenuation, were evaluated. A flat attenuation protector distorts the incoming sound less than a conventional device because approximately equal attenuation is provided across all frequencies. This is in contrast to the conventional protectors that were used, which provided more high frequency attenuation and, consequently, the balance between the low and high frequencies was altered. Flat attenuation earplugs are typically sold as hearing protection for musicians, as they are intended to maintain the music's spectral balance while providing a moderate amount of sound attenuation. Industrial workers also can benefit from these types of hearing protectors, since machine/equipment sounds can essentially be heard undistorted; however, their effects on vocal output in a noisy situation have not been studied.

Additionally, the data produced in this study were not sufficient to explain why occluding the canal right at the entrance produced different responses between the quiet and noise conditions. The exact underlying mechanism is unknown which caused a complete opposite effect whereby the earplug producing the largest occlusion effect (putty type) caused the subjects' to lower their voice levels in quiet and raise them in all background noise levels, as compared to the other two occlusion conditions.

5.4 CONCLUSIONS

This study answers the theoretical question of which aspect/characteristic of a hearing protector has the most influence on a talker's voice level. It also provides some practical information for hearing protector users regarding wearing techniques that potentially could provide some benefit in terms of better speech communication in noise.

Previous research studies often reported different effects, e.g., sometimes the talker's voice level changed slightly and other times the changes were quite large. No general rules have been developed to account for these differences. Because none of the previous studies tested the full range of hearing protector attenuation levels or carefully controlled the occlusion effect while examining the effects of different levels of noise, is it not surprising that the findings of some studies conflicted with others. All three dependent variables – occlusion type, amount of attenuation, and noise level – have an effect on the talker's voice output level, and all three must be known to fully understand and/or predict the resultant effect.

This issue is part of a larger dilemma. Workers will not consistently wear hearing protectors that are perceived to be uncomfortable or interfere with their ability to hear important sounds (Stephenson, Shaw, Stephenson, & Graydon, 2011). Although studies have demonstrated that training can effectively teach workers to properly fit and use earplugs (Joseph, Punch, Stephenson, Wolfe, Paneth, & Murphy, 2007; Murphy, Stephenson, Byrne, Witt, & Duran, 2011), there is a paucity of data regarding descriptors other than the Noise Reduction Rating

(NRR) that can be used to rate hearing protector performance. The NRR is a single-number metric representing a hearing protector's attenuation, but it does not provide any other performance characteristics of the device. The hearing health of workers may be substantially improved by providing practical information that can be used to select a protector that is comfortable and that will minimally impact their ability to hear important sounds. Differences in voice output were found among various hearing protector attenuation/occlusion conditions and background noise levels, suggesting that further investigation should be pursued. The results of this study may be used to begin an effort to quantify metrics for other aspects of a hearing protector's practical usability/wearability. By developing these performance metrics, workers will have information to make informed decisions about which hearing protector they should use for their particular work environment.

APPENDIX A

PHONETICALLY BALANCED PHRASE LISTS TYPICAL OF COMMUNICATION IN NOISY WORK ENVIRONMENTS

(Extracted from Cluff, Pavlovic, and Overson, 1993)

List # 1	List # 2	List # 3	List # 4
1. are we down	1. call that one in	1. it was like that	1. dump it out
2. attach the hose	2. clean this up	2. call your office	2. this is a rush
3. break the glass	3. plug it in	3. shut down the fan	3. go down there
4. he fell down	4. yes we have it	4. the part you took	4. it's lunch break
5. fill this out	5. you hold the flag	5. open the door	5. reset the counter
6. it's too loud	6. go ahead then	6. catch the rope	6. sight the job in
7. set the timer	7. go to the cabinet	7. finish this part	7. bore a hole
8. block the door	8. is this better	8. dam it up	8. right behind you
9. drop by my office	9. you have t-nuts	9. can they do that	9. reset the macro
10. apply the paint	10. arm the alarm	10. stay in the clear	10. I'll get it done
11. did you sign in	11. set the voltage	11. can you see me	11. will you help me
12. three more days	12. adjust the brake	12. ready to close	12. close your eyes
13. dump that waste	13. file the keyway	13. this is a new lot	13. where is he now
14. what's the length	14. crack the valve	14. alert the boss	14. I didn't do it
15. lower it down	15. check the bottle	15. what's wrong here	15. sand it off
16. block the road	16. I need a reamer	16. in the tool cage	16. bring the rope
17. air up the tires	17. not for you	17. have it inspected	17. this is terrible
18. you bet I did	18. amend the order	18. apply the torch	18. put it on rinse
19. crack the lid	19. right on course	19. beat the wall	19. this is too long
20. can you accept	20. what should I do	20. look over there	20. reset the bit

List # 5

1. clean up the mess
2. tear it apart
3. carry this box
4. hold the light
5. did it stop
6. runs good now
7. get me a drill
8. blow the horn
9. never mind then
10. fix the drill
11. was he hurt bad
12. fill up the bins
13. he’s gone fishing
14. the line is down
15. dig it up
16. fill the bottle
17. bring it here
18. go ask Jack
19. who’s not here
20. is it done yet

List # 6

1. run it slower
2. take my hand
3. place it there
4. ring the bell
5. call the job in
6. watch your step
7. belly down there
8. ask the boss
9. did it fall
10. I’m ready to go
11. where’s the paper
12. change the cutter
13. hand me the iron
14. bend the wire
15. I’m on finish cut
16. catch the wrench
17. reject this part
18. crack it open
19. ship it today
20. fix the punch

List # 7

1. set up the tool
2. go right now
3. where is it
4. pull it slower
5. I’m doing trim
6. stop the noise
7. plug the flow
8. close the gate
9. get my glasses
10. does it hurt
11. clean the machine
12. did you run it
13. fill the bucket
14. this is too big
15. block the path
16. adjust the light
17. who was that
18. it’s over there
19. approach the door
20. we’re ready now

List # 8

1. put this back
2. have a nice day
3. I need sandpaper
4. clog the spout
5. what’s the matter
6. check the heater
7. I’m going now
8. amend the call
9. try it now
10. give me a drill
11. set the macro
12. take it slower
13. change the bit
14. beam the light
15. bring the cable
16. do you hear it
17. take a break
18. approach the cart
19. where’s the rest
20. check the bead

APPENDIX B

PHRASE LIST USED IN THIS STUDY

(Adapted from List #1 in Cluff, Pavlovic, and Overson, 1993)

1. ~~are we down~~ we are down
2. attach the hose
3. break the glass
4. he fell down
5. fill this out
6. it's too loud
7. set the timer
8. block the door
9. drop by my office
10. apply the paint
11. ~~did you sign in~~ you should sign in
12. three more days
13. dump that waste
14. ~~what's the length~~ that's the length
15. lower it down
16. block the road
17. air up the tires
18. you bet I did
19. crack the lid
20. ~~can you accept~~ you can accept

APPENDIX C

RANDOMIZED SUBJECT TESTING SCHEDULE

	Occlusion Condition: Deep insertion earplug (Minimum occlusion effect)															
	Background: quiet				Background: 75 dB				Background: 85 dB				Background: 95 dB			
	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB
S1	8	12	11	1	3	2	7	9	4	14	16	10	15	5	13	6
S2	15	7	5	3	14	2	10	11	12	8	16	1	9	6	13	4
S3	3	9	14	4	12	7	10	13	5	8	11	6	15	1	2	16
S4	16	1	2	12	3	10	5	13	11	14	8	4	15	9	6	7
S5	3	5	1	6	12	13	11	7	16	2	14	10	8	15	9	4
S6	13	5	15	16	8	2	12	14	11	9	4	1	6	7	10	3
S7	13	14	3	16	9	8	11	5	4	15	12	2	10	1	7	6
S8	5	6	4	8	13	7	16	15	10	9	1	3	11	14	2	12
S9	6	5	10	12	1	4	2	3	15	16	9	13	8	14	7	11
S10	16	14	7	9	10	1	15	4	6	8	2	5	11	12	3	13
S11	11	10	13	1	12	2	15	14	9	16	6	7	8	4	3	5
S12	9	4	12	5	13	7	16	2	3	14	11	1	10	15	8	6
S13	1	13	14	4	16	7	2	8	12	15	3	11	10	9	6	5
S14	8	9	6	3	14	13	12	2	10	4	1	7	11	15	16	5
S15	9	13	15	3	12	6	10	2	4	11	16	5	7	8	1	14
S16	6	4	16	12	8	11	5	2	1	9	10	3	7	15	13	14
S17	2	12	7	13	10	14	1	5	15	6	16	9	3	8	11	4
S18	2	10	3	8	4	9	6	7	13	1	15	11	14	12	16	5

	Occlusion Condition: At earcanal entrance (Putty-type HPD, Maximum occlusion effect)															
	Background: quiet				Background: 75 dB				Background: 85 dB				Background: 95 dB			
	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB
S1	2	10	3	8	4	9	6	7	13	1	15	11	14	12	16	5
S2	15	4	10	7	5	1	8	3	12	13	9	16	14	11	2	6
S3	9	1	7	6	5	4	14	2	8	10	11	16	12	15	3	13
S4	8	6	12	5	11	15	3	2	7	10	1	16	14	4	13	9
S5	10	9	1	11	6	12	7	3	14	8	2	16	13	4	15	5
S6	15	7	6	10	3	12	14	13	9	5	2	16	4	1	8	11
S7	2	9	13	11	4	10	16	15	8	6	14	1	3	12	5	7
S8	2	1	7	12	8	9	11	10	3	16	14	15	4	5	6	13
S9	5	16	12	4	14	2	9	3	6	13	8	11	7	15	10	1
S10	10	2	11	15	12	9	6	3	13	16	4	14	5	8	7	1
S11	3	11	4	14	8	13	1	2	16	5	7	10	9	6	12	15
S12	9	2	1	3	7	8	14	4	15	11	5	10	12	13	16	6
S13	5	12	10	2	6	14	13	1	4	3	16	15	8	11	7	9
S14	8	10	1	13	15	5	2	16	7	4	3	6	9	12	11	14
S15	3	10	7	9	15	5	16	4	13	6	8	11	2	14	1	12
S16	13	3	9	8	6	2	16	11	15	10	12	4	7	14	1	5
S17	16	11	7	3	14	12	2	4	13	10	9	15	5	6	1	8
S18	6	7	15	11	9	8	12	3	5	2	1	16	4	14	10	13

	Occlusion Condition: Earmuff (Minimum occlusion effect)															
	Background: quiet				Background: 75 dB				Background: 85 dB				Background: 95 dB			
	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB	0 dB	10 dB	20 dB	30 dB
S1	8	4	12	10	16	7	5	2	3	11	9	6	14	15	13	1
S2	6	1	8	11	10	2	12	3	5	9	4	15	16	7	14	13
S3	4	9	7	16	5	13	12	2	11	8	6	14	3	1	15	10
S4	5	12	10	9	14	2	6	11	13	7	8	15	4	1	16	3
S5	7	14	5	1	15	16	4	8	3	6	10	11	13	9	12	2
S6	15	10	14	8	12	2	11	16	1	9	3	4	13	6	5	7
S7	8	14	16	11	12	7	5	1	3	15	9	6	13	2	4	10
S8	16	4	12	11	10	2	14	6	8	13	3	1	5	9	7	15
S9	6	16	15	14	11	13	2	1	9	12	5	4	10	8	3	7
S10	4	1	16	3	12	5	13	14	10	15	8	2	9	11	6	7
S11	5	4	3	8	15	9	2	6	11	14	10	1	13	16	12	7
S12	8	16	12	1	6	11	3	7	15	10	2	5	9	13	14	4
S13	13	4	3	7	11	16	15	2	9	6	10	8	1	5	14	12
S14	5	7	1	12	14	8	4	16	13	15	6	3	9	2	10	11
S15	8	6	14	11	12	1	2	7	15	5	13	3	10	4	16	9
S16	16	10	2	8	13	7	3	6	5	12	11	14	1	9	4	15
S17	10	13	9	15	3	5	1	12	8	6	14	4	7	11	2	16
S18	11	10	8	13	5	6	7	4	2	3	1	14	16	9	12	15

APPENDIX D

GENERAL LINEAR MODEL - MARGINAL MEANS

Note: α = 0.05

Effect	Atten.	Occl. type	Noise	Estimate	Std. Error	DF	t value	Pr > |t|	Lower	Upper
Occl. type		Muff		65.8616	0.8475	35	77.71	<.0001	64.1411	67.5822
Occl. type		Putty		67.0504	0.8475	35	79.11	<.0001	65.3298	68.7709
Occl. type		Foam		65.5844	0.8475	35	77.39	<.0001	63.8638	67.3049
Noise			95	68.5357	0.7907	3343	86.68	<.0001	66.9854	70.0859
Noise			85	66.6935	0.7907	3343	84.35	<.0001	65.1432	68.2438
Noise			75	65.6072	0.7907	3343	82.97	<.0001	64.0568	67.1575
Noise			0	63.8255	0.7907	3343	80.72	<.0001	62.2752	65.3758
Atten	30			66.9843	0.7907	3343	84.72	<.0001	65.4340	68.5346
Atten	20			66.7763	0.7907	3343	84.45	<.0001	65.2260	68.3266
Atten	10			66.1420	0.7907	3343	83.65	<.0001	64.5917	67.6923
Atten	0			64.7592	0.7907	3343	81.90	<.0001	63.2089	66.3095
Occl. type×Noise		Muff	95	67.8846	0.8521	3343	79.67	<.0001	66.2140	69.5552
Occl. type×Noise		Muff	85	66.2248	0.8521	3343	77.72	<.0001	64.5542	67.8955
Occl. type×Noise		Muff	75	65.0930	0.8523	3343	76.38	<.0001	63.4220	66.7641
Occl. type×Noise		Muff	0	64.2440	0.8521	3343	75.40	<.0001	62.5734	65.9146
Occl. type×Noise		Putty	95	70.4044	0.8521	3343	82.63	<.0001	68.7338	72.0751

Effect	Atten.	Occl. type	Noise	Estimate	Std. Error	DF	t value	Pr > |t|	Lower	Upper
Occl. type×Noise		Putty	85	67.9803	0.8521	3343	79.78	<.0001	66.3097	69.6509
Occl. type×Noise		Putty	75	66.5359	0.8521	3343	78.09	<.0001	64.8653	68.2065
Occl. type×Noise		Putty	0	63.2809	0.8521	3343	74.27	<.0001	61.6103	64.9515
Occl. type×Noise		Foam	95	67.3180	0.8521	3343	79.01	<.0001	65.6473	68.9886
Occl. type×Noise		Foam	85	65.8754	0.8521	3343	77.31	<.0001	64.2048	67.5460
Occl. type×Noise		Foam	75	65.1926	0.8521	3343	76.51	<.0001	63.5220	66.8632
Occl. type×Noise		Foam	0	63.9516	0.8521	3343	75.06	<.0001	62.2810	65.6222
Atten×Occl. type	30	Muff		66.9862	0.8521	3343	78.61	<.0001	65.3155	68.6568
Atten×Occl. type	30	Putty		67.7201	0.8521	3343	79.48	<.0001	66.0494	69.3907
Atten×Occl. type	30	Foam		66.2468	0.8521	3343	77.75	<.0001	64.5762	67.9174
Atten×Occl. type	20	Muff		66.6185	0.8521	3343	78.19	<.0001	64.9478	68.2891
Atten×Occl. type	20	Putty		67.4895	0.8521	3343	79.21	<.0001	65.8189	69.1601
Atten×Occl. type	20	Foam		66.2210	0.8521	3343	77.72	<.0001	64.5504	67.8916
Atten×Occl. type	10	Muff		65.7456	0.8523	3343	77.14	<.0001	64.0746	67.4166
Atten×Occl. type	10	Putty		67.1868	0.8521	3343	78.85	<.0001	65.5162	68.8574
Atten×Occl. type	10	Foam		65.4936	0.8521	3343	76.86	<.0001	63.8230	67.1642
Atten×Occl. type	0	Muff		64.0962	0.8521	3343	75.23	<.0001	62.4256	65.7668
Atten×Occl. type	0	Putty		65.8051	0.8521	3343	77.23	<.0001	64.1345	67.4758
Atten×Occl. type	0	Foam		64.3761	0.8521	3343	75.55	<.0001	62.7055	66.0467
Atten×Noise	30		95	69.3339	0.7972	3343	86.97	<.0001	67.7708	70.8969
Atten×Noise	30		85	67.7365	0.7972	3343	84.96	<.0001	66.1734	69.2996
Atten×Noise	30		75	66.3509	0.7972	3343	83.23	<.0001	64.7879	67.9139

Effect	Atten.	Occl. type	Noise	Estimate	Std. Error	DF	t value	Pr > |t|	Lower	Upper
Atten×Noise	30		0	64.5160	0.7972	3343	80.93	<.0001	62.9530	66.0791
Atten×Noise	20		95	69.2496	0.7972	3343	86.87	<.0001	67.6865	70.8126
Atten×Noise	20		85	67.4795	0.7972	3343	84.65	<.0001	65.9164	69.0425
Atten×Noise	20		75	66.2022	0.7972	3343	83.04	<.0001	64.6392	67.7653
Atten×Noise	20		0	64.1741	0.7972	3343	80.50	<.0001	62.6111	65.7371
Atten×Noise	10		95	68.5751	0.7972	3343	86.02	<.0001	67.0121	70.1381
Atten×Noise	10		85	66.4726	0.7972	3343	83.38	<.0001	64.9096	68.0356
Atten×Noise	10		75	65.5725	0.7976	3343	82.22	<.0001	64.0087	67.1363
Atten×Noise	10		0	63.9478	0.7972	3343	80.22	<.0001	62.3848	65.5109
Atten×Noise	0		95	66.9841	0.7972	3343	84.02	<.0001	65.4210	68.5472
Atten×Noise	0		85	65.0855	0.7972	3343	81.64	<.0001	63.5224	66.6485
Atten×Noise	0		75	64.3030	0.7972	3343	80.66	<.0001	62.7400	65.8660
Atten×Noise	0		0	62.6640	0.7972	3343	78.61	<.0001	61.1010	64.2271

D.1 TESTS OF EFFECT SLICES

Effect	Occl. type	Noise	Numerator Degrees of Freedom	Denominator Degrees of Freedom	F Value	Pr > F
Occl. type×Noise	Muff		3	3343	239.45	<.0001
Occl. type×Noise	Putty		3	3343	857.65	<.0001
Occl. type×Noise	Foam		3	3343	190.91	<.0001
Atten×Occl. type	Muff		3	3343	160.32	<.0001
Atten×Occl. type	Putty		3	3343	71.24	<.0001
Atten×Occl. type	Foam		3	3343	74.70	<.0001
Occl. type×Noise		95	2	3343	17.85	<.0001
Occl. type×Noise		85	2	3343	8.41	0.0002
Occl. type×Noise		75	2	3343	4.29	0.0138
Occl. type×Noise		0	2	3343	1.61	0.1996
Atten×Noise		95	3	3343	85.87	<.0001
Atten×Noise		85	3	3343	105.03	<.0001
Atten×Noise		75	3	3343	63.22	<.0001
Atten×Noise		0	3	3343	47.55	<.0001

APPENDIX E

DIFFERENCES OF MARGINAL MEANS FOR DIFFERENT OCCLUSION TYPES AND NOISE LEVELS

Occlusion Type	Noise	Occlusion Type	Noise	Estimate	Standard Error	DF	t Value	Pr > |t|	Tukey-Kramer adjusted p-value
Muff	95	Muff	85	1.6597	0.1438	3343	11.54	<.0001	<.0001
Muff	95	Muff	75	2.7915	0.1448	3343	19.27	<.0001	<.0001
Muff	95	Muff	0	3.6406	0.1437	3343	25.34	<.0001	<.0001
Muff	95	Putty	95	-2.5198	0.5500	3343	-4.58	<.0001	0.0003
Muff	95	Putty	85	-0.09573	0.5499	3343	-0.17	0.8618	1.0000
Muff	95	Putty	75	1.3487	0.5499	3343	2.45	0.0142	0.3708
Muff	95	Putty	0	4.6037	0.5499	3343	8.37	<.0001	<.0001
Muff	95	Foam	95	0.5666	0.5499	3343	1.03	0.3029	0.9970
Muff	95	Foam	85	2.0092	0.5499	3343	3.65	0.0003	0.0139
Muff	95	Foam	75	2.6920	0.5499	3343	4.90	<.0001	<.0001
Muff	95	Foam	0	3.9330	0.5499	3343	7.15	<.0001	<.0001
Muff	85	Muff	75	1.1318	0.1450	3343	7.81	<.0001	<.0001
Muff	85	Muff	0	1.9808	0.1438	3343	13.78	<.0001	<.0001
Muff	85	Putty	95	-4.1796	0.5500	3343	-7.60	<.0001	<.0001
Muff	85	Putty	85	-1.7555	0.5500	3343	-3.19	0.0014	0.0634
Muff	85	Putty	75	-0.3110	0.5500	3343	-0.57	0.5718	1.0000
Muff	85	Putty	0	2.9439	0.5500	3343	5.35	<.0001	<.0001
Muff	85	Foam	95	-1.0931	0.5500	3343	-1.99	0.0469	0.7021
Muff	85	Foam	85	0.3495	0.5500	3343	0.64	0.5252	1.0000
Muff	85	Foam	75	1.0323	0.5500	3343	1.88	0.0606	0.7737

Occlusion Type	Noise	Occlusion Type	Noise	Estimate	Standard Error	DF	t Value	Pr > |t|	Tukey-Kramer adjusted p-value
Muff	85	Foam	0	2.2733	0.5500	3343	4.13	<.0001	0.0022
Muff	75	Muff	0	0.8490	0.1448	3343	5.86	<.0001	<.0001
Muff	75	Putty	95	-5.3114	0.5503	3343	-9.65	<.0001	<.0001
Muff	75	Putty	85	-2.8873	0.5503	3343	-5.25	<.0001	<.0001
Muff	75	Putty	75	-1.4428	0.5503	3343	-2.62	0.0088	0.2675
Muff	75	Putty	0	1.8121	0.5503	3343	3.29	0.0010	0.0466
Muff	75	Foam	95	-2.2249	0.5503	3343	-4.04	<.0001	0.0031
Muff	75	Foam	85	-0.7823	0.5503	3343	-1.42	0.1552	0.9595
Muff	75	Foam	75	-0.09952	0.5503	3343	-0.18	0.8565	1.0000
Muff	75	Foam	0	1.1415	0.5503	3343	2.07	0.0381	0.6413
Muff	0	Putty	95	-6.1604	0.5500	3343	-11.20	<.0001	<.0001
Muff	0	Putty	85	-3.7363	0.5499	3343	-6.79	<.0001	<.0001
Muff	0	Putty	75	-2.2919	0.5499	3343	-4.17	<.0001	0.0019
Muff	0	Putty	0	0.9631	0.5499	3343	1.75	0.0800	0.8440
Muff	0	Foam	95	-3.0739	0.5499	3343	-5.59	<.0001	<.0001
Muff	0	Foam	85	-1.6314	0.5499	3343	-2.97	0.0030	0.1190
Muff	0	Foam	75	-0.9486	0.5499	3343	-1.72	0.0847	0.8570
Muff	0	Foam	0	0.2924	0.5499	3343	0.53	0.5949	1.0000
Putty	95	Putty	85	2.4241	0.1438	3343	16.86	<.0001	<.0001
Putty	95	Putty	75	3.8686	0.1438	3343	26.91	<.0001	<.0001
Putty	95	Putty	0	7.1235	0.1438	3343	49.54	<.0001	<.0001
Putty	95	Foam	95	3.0865	0.5500	3343	5.61	<.0001	<.0001
Putty	95	Foam	85	4.5290	0.5500	3343	8.23	<.0001	<.0001
Putty	95	Foam	75	5.2119	0.5500	3343	9.48	<.0001	<.0001
Putty	95	Foam	0	6.4528	0.5500	3343	11.73	<.0001	<.0001
Putty	85	Putty	75	1.4444	0.1437	3343	10.06	<.0001	<.0001
Putty	85	Putty	0	4.6994	0.1437	3343	32.71	<.0001	<.0001
Putty	85	Foam	95	0.6624	0.5499	3343	1.20	0.2285	0.9887
Putty	85	Foam	85	2.1049	0.5499	3343	3.83	0.0001	0.0073
Putty	85	Foam	75	2.7877	0.5499	3343	5.07	<.0001	<.0001
Putty	85	Foam	0	4.0287	0.5499	3343	7.33	<.0001	<.0001
Putty	75	Putty	0	3.2549	0.1437	3343	22.66	<.0001	<.0001
Putty	75	Foam	95	-0.7821	0.5499	3343	-1.42	0.1551	0.9594
Putty	75	Foam	85	0.6605	0.5499	3343	1.20	0.2298	0.9890

Occlusion Type	Noise	Occlusion Type	Noise	Estimate	Standard Error	DF	t Value	Pr > |t|	Tukey-Kramer adjusted p-value
Putty	75	Foam	75	1.3433	0.5499	3343	2.44	0.0146	0.3774
Putty	75	Foam	0	2.5843	0.5499	3343	4.70	<.0001	0.0002
Putty	0	Foam	95	-4.0370	0.5499	3343	-7.34	<.0001	<.0001
Putty	0	Foam	85	-2.5945	0.5499	3343	-4.72	<.0001	0.0002
Putty	0	Foam	75	-1.9116	0.5499	3343	-3.48	0.0005	0.0258
Putty	0	Foam	0	-0.6707	0.5499	3343	-1.22	0.2227	0.9875
Foam	95	Foam	85	1.4426	0.1437	3343	10.04	<.0001	<.0001
Foam	95	Foam	75	2.1254	0.1437	3343	14.80	<.0001	<.0001
Foam	95	Foam	0	3.3664	0.1437	3343	23.43	<.0001	<.0001
Foam	85	Foam	75	0.6828	0.1437	3343	4.75	<.0001	0.0001
Foam	85	Foam	0	1.9238	0.1437	3343	13.39	<.0001	<.0001
Foam	75	Foam	0	1.2410	0.1437	3343	8.64	<.0001	<.0001

APPENDIX F

DIFFERENCES OF MARGINAL MEANS FOR DIFFERENT LEVELS OF ATTENUATION AND NOISE

Atten.	Noise	Atten.	Noise	Estimate	Standard Error	DF	t Value	Pr > |t|	Tukey-Kramer adjusted p-value
30	95	30	85	1.5974	0.1661	3343	9.62	<.0001	<.0001
30	95	30	75	2.9830	0.1659	3343	17.98	<.0001	<.0001
30	95	30	0	4.8178	0.1659	3343	29.04	<.0001	<.0001
30	95	20	95	0.08432	0.1659	3343	0.51	0.6113	1.0000
30	95	20	85	1.8544	0.1659	3343	11.18	<.0001	<.0001
30	95	20	75	3.1316	0.1659	3343	18.88	<.0001	<.0001
30	95	20	0	5.1598	0.1659	3343	31.11	<.0001	<.0001
30	95	10	95	0.7588	0.1659	3343	4.57	<.0001	0.0006
30	95	10	85	2.8613	0.1659	3343	17.25	<.0001	<.0001
30	95	10	75	3.7614	0.1677	3343	22.43	<.0001	<.0001
30	95	10	0	5.3860	0.1659	3343	32.47	<.0001	<.0001
30	95	0	95	2.3498	0.1661	3343	14.15	<.0001	<.0001
30	95	0	85	4.2484	0.1659	3343	25.61	<.0001	<.0001
30	95	0	75	5.0309	0.1659	3343	30.33	<.0001	<.0001
30	95	0	0	6.6698	0.1659	3343	40.21	<.0001	<.0001
30	85	30	75	1.3856	0.1661	3343	8.34	<.0001	<.0001
30	85	30	0	3.2205	0.1661	3343	19.39	<.0001	<.0001
30	85	20	95	-1.5131	0.1661	3343	-9.11	<.0001	<.0001
30	85	20	85	0.2570	0.1661	3343	1.55	0.1218	0.9768
30	85	20	75	1.5343	0.1661	3343	9.24	<.0001	<.0001

Atten.	Noise	Atten.	Noise	Estimate	Standard Error	DF	t Value	Pr > |t|	Tukey-Kramer adjusted p-value
30	85	20	0	3.5624	0.1661	3343	21.45	<.0001	<.0001
30	85	10	95	-0.8386	0.1661	3343	-5.05	<.0001	<.0001
30	85	10	85	1.2639	0.1661	3343	7.61	<.0001	<.0001
30	85	10	75	2.1640	0.1679	3343	12.89	<.0001	<.0001
30	85	10	0	3.7887	0.1661	3343	22.81	<.0001	<.0001
30	85	0	95	0.7524	0.1663	3343	4.53	<.0001	0.0007
30	85	0	85	2.6510	0.1661	3343	15.96	<.0001	<.0001
30	85	0	75	3.4335	0.1661	3343	20.67	<.0001	<.0001
30	85	0	0	5.0725	0.1661	3343	30.54	<.0001	<.0001
30	75	30	0	1.8349	0.1659	3343	11.06	<.0001	<.0001
30	75	20	95	-2.8986	0.1659	3343	-17.47	<.0001	<.0001
30	75	20	85	-1.1285	0.1659	3343	-6.80	<.0001	<.0001
30	75	20	75	0.1487	0.1659	3343	0.90	0.3701	1.0000
30	75	20	0	2.1768	0.1659	3343	13.12	<.0001	<.0001
30	75	10	95	-2.2242	0.1659	3343	-13.41	<.0001	<.0001
30	75	10	85	-0.1217	0.1659	3343	-0.73	0.4632	1.0000
30	75	10	75	0.7784	0.1677	3343	4.64	<.0001	0.0004
30	75	10	0	2.4031	0.1659	3343	14.49	<.0001	<.0001
30	75	0	95	-0.6332	0.1661	3343	-3.81	0.0001	0.0133
30	75	0	85	1.2654	0.1659	3343	7.63	<.0001	<.0001
30	75	0	75	2.0479	0.1659	3343	12.35	<.0001	<.0001
30	75	0	0	3.6869	0.1659	3343	22.23	<.0001	<.0001
30	0	20	95	-4.7335	0.1659	3343	-28.54	<.0001	<.0001
30	0	20	85	-2.9634	0.1659	3343	-17.87	<.0001	<.0001
30	0	20	75	-1.6862	0.1659	3343	-10.17	<.0001	<.0001
30	0	20	0	0.3419	0.1659	3343	2.06	0.0393	0.7897
30	0	10	95	-4.0591	0.1659	3343	-24.47	<.0001	<.0001
30	0	10	85	-1.9566	0.1659	3343	-11.80	<.0001	<.0001
30	0	10	75	-1.0564	0.1677	3343	-6.30	<.0001	<.0001
30	0	10	0	0.5682	0.1659	3343	3.43	0.0006	0.0505
30	0	0	95	-2.4681	0.1661	3343	-14.86	<.0001	<.0001
30	0	0	85	-0.5694	0.1659	3343	-3.43	0.0006	0.0493
30	0	0	75	0.2130	0.1659	3343	1.28	0.1991	0.9964
30	0	0	0	1.8520	0.1659	3343	11.16	<.0001	<.0001

Atten.	Noise	Atten.	Noise	Estimate	Standard Error	DF	t Value	Pr > |t|	Tukey-Kramer adjusted p-value
20	95	20	85	1.7701	0.1659	3343	10.67	<.0001	<.0001
20	95	20	75	3.0473	0.1659	3343	18.37	<.0001	<.0001
20	95	20	0	5.0754	0.1659	3343	30.60	<.0001	<.0001
20	95	10	95	0.6745	0.1659	3343	4.07	<.0001	0.0050
20	95	10	85	2.7769	0.1659	3343	16.74	<.0001	<.0001
20	95	10	75	3.6771	0.1677	3343	21.93	<.0001	<.0001
20	95	10	0	5.3017	0.1659	3343	31.96	<.0001	<.0001
20	95	0	95	2.2655	0.1661	3343	13.64	<.0001	<.0001
20	95	0	85	4.1641	0.1659	3343	25.10	<.0001	<.0001
20	95	0	75	4.9465	0.1659	3343	29.82	<.0001	<.0001
20	95	0	0	6.5855	0.1659	3343	39.70	<.0001	<.0001
20	85	20	75	1.2772	0.1659	3343	7.70	<.0001	<.0001
20	85	20	0	3.3053	0.1659	3343	19.93	<.0001	<.0001
20	85	10	95	-1.0956	0.1659	3343	-6.61	<.0001	<.0001
20	85	10	85	1.0068	0.1659	3343	6.07	<.0001	<.0001
20	85	10	75	1.9070	0.1677	3343	11.37	<.0001	<.0001
20	85	10	0	3.5316	0.1659	3343	21.29	<.0001	<.0001
20	85	0	95	0.4954	0.1661	3343	2.98	0.0029	0.1766
20	85	0	85	2.3940	0.1659	3343	14.43	<.0001	<.0001
20	85	0	75	3.1764	0.1659	3343	19.15	<.0001	<.0001
20	85	0	0	4.8154	0.1659	3343	29.03	<.0001	<.0001
20	75	20	0	2.0281	0.1659	3343	12.23	<.0001	<.0001
20	75	10	95	-2.3729	0.1659	3343	-14.31	<.0001	<.0001
20	75	10	85	-0.2704	0.1659	3343	-1.63	0.1032	0.9630
20	75	10	75	0.6297	0.1677	3343	3.76	0.0002	0.0164
20	75	10	0	2.2544	0.1659	3343	13.59	<.0001	<.0001
20	75	0	95	-0.7819	0.1661	3343	-4.71	<.0001	0.0003
20	75	0	85	1.1168	0.1659	3343	6.73	<.0001	<.0001
20	75	0	75	1.8992	0.1659	3343	11.45	<.0001	<.0001
20	75	0	0	3.5382	0.1659	3343	21.33	<.0001	<.0001
20	0	10	95	-4.4010	0.1659	3343	-26.53	<.0001	<.0001
20	0	10	85	-2.2985	0.1659	3343	-13.86	<.0001	<.0001
20	0	10	75	-1.3984	0.1677	3343	-8.34	<.0001	<.0001
20	0	10	0	0.2263	0.1659	3343	1.36	0.1726	0.9933

Atten.	Noise	Atten.	Noise	Estimate	Standard Error	DF	t Value	Pr > |t|	Tukey-Kramer adjusted p-value
20	0	0	95	-2.8100	0.1661	3343	-16.92	<.0001	<.0001
20	0	0	85	-0.9114	0.1659	3343	-5.49	<.0001	<.0001
20	0	0	75	-0.1289	0.1659	3343	-0.78	0.4371	1.0000
20	0	0	0	1.5101	0.1659	3343	9.10	<.0001	<.0001
10	95	10	85	2.1025	0.1659	3343	12.68	<.0001	<.0001
10	95	10	75	3.0026	0.1677	3343	17.90	<.0001	<.0001
10	95	10	0	4.6272	0.1659	3343	27.90	<.0001	<.0001
10	95	0	95	1.5910	0.1661	3343	9.58	<.0001	<.0001
10	95	0	85	3.4896	0.1659	3343	21.04	<.0001	<.0001
10	95	0	75	4.2721	0.1659	3343	25.75	<.0001	<.0001
10	95	0	0	5.9111	0.1659	3343	35.64	<.0001	<.0001
10	85	10	75	0.9001	0.1677	3343	5.37	<.0001	<.0001
10	85	10	0	2.5248	0.1659	3343	15.22	<.0001	<.0001
10	85	0	95	-0.5115	0.1661	3343	-3.08	0.0021	0.1379
10	85	0	85	1.3871	0.1659	3343	8.36	<.0001	<.0001
10	85	0	75	2.1696	0.1659	3343	13.08	<.0001	<.0001
10	85	0	0	3.8086	0.1659	3343	22.96	<.0001	<.0001
10	75	10	0	1.6246	0.1677	3343	9.69	<.0001	<.0001
10	75	0	95	-1.4116	0.1679	3343	-8.41	<.0001	<.0001
10	75	0	85	0.4870	0.1677	3343	2.90	0.0037	0.2134
10	75	0	75	1.2695	0.1677	3343	7.57	<.0001	<.0001
10	75	0	0	2.9084	0.1677	3343	17.34	<.0001	<.0001
10	0	0	95	-3.0363	0.1661	3343	-18.28	<.0001	<.0001
10	0	0	85	-1.1376	0.1659	3343	-6.86	<.0001	<.0001
10	0	0	75	-0.3552	0.1659	3343	-2.14	0.0323	0.7382
10	0	0	0	1.2838	0.1659	3343	7.74	<.0001	<.0001
0	95	0	85	1.8986	0.1661	3343	11.43	<.0001	<.0001
0	95	0	75	2.6811	0.1661	3343	16.14	<.0001	<.0001
0	95	0	0	4.3201	0.1661	3343	26.01	<.0001	<.0001
0	85	0	75	0.7825	0.1659	3343	4.72	<.0001	0.0003
0	85	0	0	2.4214	0.1659	3343	14.60	<.0001	<.0001
0	75	0	0	1.6390	0.1659	3343	9.88	<.0001	<.0001

APPENDIX G

DIFFERENCES OF MARGINAL MEANS FOR DIFFERENT ATTENUATION LEVELS AND OCCLUSION TYPES

Atten.	Occlusion	Atten.	Occlusion	Estimate	Standard Error	DF	t Value	p-value|	Tukey-Kramer Adjusted p-value
30	Earmuff	30	Putty	-0.7339	0.5500	3343	-1.33	0.1822	0.9747
30	Earmuff	30	Foam	0.7394	0.5500	3343	1.34	0.1789	0.9732
30	Earmuff	20	Earmuff	0.3677	0.1438	3343	2.56	0.0106	0.3047
30	Earmuff	20	Putty	-0.5034	0.5500	3343	-0.92	0.3601	0.9990
30	Earmuff	20	Foam	0.7651	0.5500	3343	1.39	0.1642	0.9654
30	Earmuff	10	Earmuff	1.2405	0.1450	3343	8.56	<.0001	<.0001
30	Earmuff	10	Putty	-0.2007	0.5500	3343	-0.36	0.7152	1.0000
30	Earmuff	10	Foam	1.4926	0.5500	3343	2.71	0.0067	0.2196
30	Earmuff	0	Earmuff	2.8899	0.1438	3343	20.10	<.0001	<.0001
30	Earmuff	0	Putty	1.1811	0.5500	3343	2.15	0.0318	0.5884
30	Earmuff	0	Foam	2.6100	0.5500	3343	4.75	<.0001	0.0001
30	Putty	30	Foam	1.4733	0.5499	3343	2.68	0.0074	0.2371
30	Putty	20	Earmuff	1.1016	0.5499	3343	2.00	0.0452	0.6915
30	Putty	20	Putty	0.2305	0.1437	3343	1.60	0.1086	0.9077
30	Putty	20	Foam	1.4990	0.5499	3343	2.73	0.0064	0.2139
30	Putty	10	Earmuff	1.9744	0.5503	3343	3.59	0.0003	0.0176
30	Putty	10	Putty	0.5332	0.1437	3343	3.71	0.0002	0.0113
30	Putty	10	Foam	2.2265	0.5499	3343	4.05	<.0001	0.0031
30	Putty	0	Earmuff	3.6238	0.5499	3343	6.59	<.0001	<.0001

Atten.	Occlusion	Atten.	Occlusion	Estimate	Standard Error	DF	t Value	p-value|	Tukey-Kramer Adjusted p-value
30	Putty	0	Putty	1.9149	0.1438	3343	13.32	<.0001	<.0001
30	Putty	0	Foam	3.3439	0.5499	3343	6.08	<.0001	<.0001
30	Foam	20	Earmuff	-0.3717	0.5499	3343	-0.68	0.4992	0.9999
30	Foam	20	Putty	-1.2428	0.5499	3343	-2.26	0.0239	0.5059
30	Foam	20	Foam	0.02575	0.1437	3343	0.18	0.8577	1.0000
30	Foam	10	Earmuff	0.5011	0.5503	3343	0.91	0.3625	0.9990
30	Foam	10	Putty	-0.9401	0.5499	3343	-1.71	0.0875	0.8643
30	Foam	10	Foam	0.7532	0.1437	3343	5.24	<.0001	<.0001
30	Foam	0	Earmuff	2.1505	0.5499	3343	3.91	<.0001	0.0053
30	Foam	0	Putty	0.4417	0.5500	3343	0.80	0.4220	0.9997
30	Foam	0	Foam	1.8707	0.1437	3343	13.02	<.0001	<.0001
20	Earmuff	20	Putty	-0.8711	0.5499	3343	-1.58	0.1133	0.9151
20	Earmuff	20	Foam	0.3974	0.5499	3343	0.72	0.4699	0.9999
20	Earmuff	10	Earmuff	0.8728	0.1448	3343	6.03	<.0001	<.0001
20	Earmuff	10	Putty	-0.5684	0.5499	3343	-1.03	0.3014	0.9969
20	Earmuff	10	Foam	1.1249	0.5499	3343	2.05	0.0409	0.6619
20	Earmuff	0	Earmuff	2.5222	0.1437	3343	17.56	<.0001	<.0001
20	Earmuff	0	Putty	0.8133	0.5500	3343	1.48	0.1393	0.9464
20	Earmuff	0	Foam	2.2423	0.5499	3343	4.08	<.0001	0.0027
20	Putty	20	Foam	1.2685	0.5499	3343	2.31	0.0211	0.4719
20	Putty	10	Earmuff	1.7439	0.5503	3343	3.17	0.0015	0.0677
20	Putty	10	Putty	0.3027	0.1437	3343	2.11	0.0352	0.6177
20	Putty	10	Foam	1.9960	0.5499	3343	3.63	0.0003	0.0152
20	Putty	0	Earmuff	3.3933	0.5499	3343	6.17	<.0001	<.0001
20	Putty	0	Putty	1.6844	0.1438	3343	11.72	<.0001	<.0001
20	Putty	0	Foam	3.1134	0.5499	3343	5.66	<.0001	<.0001
20	Foam	10	Earmuff	0.4754	0.5503	3343	0.86	0.3877	0.9994
20	Foam	10	Putty	-0.9658	0.5499	3343	-1.76	0.0791	0.8415
20	Foam	10	Foam	0.7274	0.1437	3343	5.06	<.0001	<.0001
20	Foam	0	Earmuff	2.1248	0.5499	3343	3.86	0.0001	0.0064
20	Foam	0	Putty	0.4159	0.5500	3343	0.76	0.4496	0.9998
20	Foam	0	Foam	1.8449	0.1437	3343	12.84	<.0001	<.0001
10	Earmuff	10	Putty	-1.4412	0.5503	3343	-2.62	0.0089	0.2691

Atten.	Occlusion	Atten.	Occlusion	Estimate	Standard Error	DF	t Value	p-value|	Tukey-Kramer Adjusted p-value
10	Earmuff	10	Foam	0.2521	0.5503	3343	0.46	0.6469	1.0000
10	Earmuff	0	Earmuff	1.6494	0.1448	3343	11.39	<.0001	<.0001
10	Earmuff	0	Putty	-0.05949	0.5503	3343	-0.11	0.9139	1.0000
10	Earmuff	0	Foam	1.3695	0.5503	3343	2.49	0.0129	0.3472
10	Putty	10	Foam	1.6933	0.5499	3343	3.08	0.0021	0.0877
10	Putty	0	Earmuff	3.0906	0.5499	3343	5.62	<.0001	<.0001
10	Putty	0	Putty	1.3817	0.1438	3343	9.61	<.0001	<.0001
10	Putty	0	Foam	2.8107	0.5499	3343	5.11	<.0001	<.0001
10	Foam	0	Earmuff	1.3973	0.5499	3343	2.54	0.0111	0.3147
10	Foam	0	Putty	-0.3115	0.5500	3343	-0.57	0.5711	1.0000
10	Foam	0	Foam	1.1174	0.1437	3343	7.78	<.0001	<.0001
0	Earmuff	0	Putty	-1.7089	0.5500	3343	-3.11	0.0019	0.0810
0	Earmuff	0	Foam	-0.2799	0.5499	3343	-0.51	0.6108	1.0000
0	Putty	0	Foam	1.4290	0.5500	3343	2.60	0.0094	0.2809

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