THE EFFECTS OF HEARING PROTECTION ON SPEECH DISCRIMINATION IN DIFFERING NOISE SPECTRA

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(ABSTRACT)

This research project was aimed at investigation of speech communication issues in industrial noise environments where workers utilize hearing protection devices (HPDs).

A controlled empirical study was conducted to determine the effects of several independent variables on speech reception and discrimination including: 1). subject's hearing configuration (unoccluded or earplug, earcap, earmuff-occluded), 2). ambient noise intensity level (60, 83 dBA), 3). ambient noise spectral type (low, white approximation, high frequency), 4). speaker's voice level (63 or 65 dBA in 60 dBA noise, 82 or 88 dBA in 83 dBA noise), and 5). subject's hearing level (normal hearing, slight loss, or moderate loss) used as a blocking variable. Isophonemic word discrimination, with male-voiced word lists presented through loudspeakers in an anechoic field, served as the experimental task. Twenty-three males and twenty-two females participated in the experiment and a mixed-factors, partial hierarchical design was used for data collection. Analysis of variance and Newman-Keuls multiple-range tests were applied to the data.

All main effects, with the exception of hearing level blocks, were significant, in addition to several interactions. These are discussed in detail and depicted graphically. One fundamental finding was that none of the hearing protection devices degraded speech discrimination (in comparison to an unoccluded condition) in the 83 dBA ambient noise level. In fact, the most protective HPD significantly enhanced speech discrimination in the high noise level. In the low ambient noise level, there was some reduction in discrimination due to the wearing of an HPD, but this effect is not of concern because HPDs are not needed at low ambient levels for protection purposes. From the results, it appears that properly selected HPDs can be expected to at least maintain speech discrimination levels (equivalent to unoccluded levels) in moderately-high intensity industrial noises of varied spectral characteristics.

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INTRODUCTION

Background

The adverse effects of exposure to work-related noise are a topic of great concern for employees and industrial management alike. Intense noise, which is prominent in many industries, can cause temporary and/or permanent hearing loss if workers are not adequately protected. Hearing conservation programs, which attempt to reduce the debilitating effects of industrial noise, have emphasized the use of hearing protection devices (HPDs). If properly administered and used, HPDs provide an effective and economical solution to the adverse effects of intense sound. One important consideration in industrial HPD usage is their effect on speech communication between workers. HPDs effectively reduce sound levels (of both speech and noise) introduced to the ear. As such, HPDs have been claimed by some to hinder speech communication, such as job instructions, verbal warnings, and routine conversation. An investigation of this effect constituted the essence of the research described herein.

Noise-induced hearing loss. Exposure to high intensity industrial noise has resulted in permanent hearing loss for millions of workers. For instance, in the age group of 50 to 59 years alone, it is estimated that 1.7 million workers have suffered hearing loss as a result of enduring high levels of noise (Robinette, 1984). Furthermore, Miller (1978) reports that more people suffer from occupational hearing loss than all other occupational infirmities combined. The major source of offending noise is industrial machines; for instance, over half of those surveyed (by Cheremisinoff and Cheremisinoff, 1978) produced noise levels of 90 to 100 decibels (dB), which is well into the danger zone.

Exposure to intense sound may cause a loss in hearing which is indicated by an elevation in the hearing threshold. An acute case of noise-induced hearing loss is known as a temporary threshold shift (TTS). The magnitude of TTS is greatest just after sound exposure, although hearing is recoverable with time away from the source (Tempest, 1985). On the other hand, long-term or repeated exposures to intense sound levels may result in noise induced permanent threshold shift (NIPTS). NIPTS is characterized by an insidious onset and a cumulative progression and thus often goes unnoticed by the victim until the degradation in speech intelligibility is markedly apparent. NIPTS constitutes a physical impairment which is permanent and incurable, and a pronounced social disability which isolates the afflicted individual from family and friends. For industry, the cost of NIPTS is measured financially in the form of workers' compensation claims, costing millions of dollars (Robinette, 1984) and increasing at the rate of approximately 20% per year.

In response to this growing problem, the United States Occupational Safety and Health Administration (OSHA) has established a regulation (Code of Federal Regulations 1910.95) which limits the workers' exposure time to 8 hours per day of 90 dBA (time-weighted average) noise levels (OSHA, 1985). In addition, the regulation requires that a hearing conservation program be implemented whenever employee daily noise exposures are equal to or exceed 8-hours of 85 dBA (time-weighted average) noise intensity. (Sound pressure levels measured in the A frequency-response weighting network are most representative, as compared to the B and C scales, of the response characteristics of the human ear as noted, for instance, by McCormick and Sanders, 1982.)

Hearing protection devices (HPDs). The most popular countermeasure against NIPTS in the industrial setting is the use of personal hearing protection devices (Melnick, 1984). HPDs are popular because of their effectiveness in noise reduction, ease of use and administration, and because they are, at this time, an economically-feasible alternative to some engineering and administrative controls (Abel, Alberti, Haythornthwaite, and Riko, 1982). However, the usefulness of HPDs has been somewhat hindered with problems such as lack of wearer motivation, improper application, misuse, abuse, and discomfort (Berger, 1982a; Riko and Alberti, 1981). In addition, the practicality of HPDs has been challenged by some industrial workers and others who claim that HPDs interfere with effective speech communication (Lindeman, 1971) and with the detection of warning signals (Michael, 1965).

The protective effectiveness of an HPD is measured by the extent to which it reduces the level of sound reaching the ear (Else, 1973), with each device having its own unique spectral attenuation characteristics. The attenuation provided by HPD usage will reduce speech as well as noise to the same degree when the two sounds have similar spectral characteristics (Kryter, 1946). Thus, the attenuation afforded by an HPD can, in addition to reducing the level of unwanted sounds, reduce the intelligibility of spoken messages between HPD wearers. Therefore, the effects of HPD usage on the reception and discrimination of speech in noise conditions are of major concern. This is especially true in industrial environments where effective communication, such as verbal warnings of impending danger, can be critical to workers' safety and job productivity. The HPD-communication issue is also becoming a problem of greater significance with the advent of voice recognition/synthesis systems being introduced into the workplace.

The following literature review addresses several factors which have bearing on speech communication performance in noisy environments. The primary factor of interest in the research described herein concerned the effect of HPDs on communication. Other contributing factors are also reviewed in the context of their influence on speech communication.

INDUSTRIAL FACTORS AFFECTING VERBAL COMMUNICATION

Preliminary Issues

Several factors which are present in an industrial environment, in addition to HPDs, are also known to affect the transmission, reception, and discrimination of speech sounds. Some of these factors include: ambient noise intensity level, signal (speech)-to-noise (S/N) ratio, ambient noise spectral characteristics, ambient noise temporal characteristics, and individual's degree of hearing loss. If the noise conditions present in an environment warrant the use of HPDs, then the appropriate selection of an HPD type cannot be complete without a consideration of these additional factors. An inappropriate type of HPD can result in inadequate hearing protection and/or unnecessarily reduced speech intelligibility, both of which affect the safety and welfare of industrial workers. The present study investigated the degree to which recognition and discrimination of spoken words are dependent on the type of HPD used, ambient noise intensity level, speaker's (talker's) voice level, and noise spectrum, while controlling for differences in listeners' hearing acuity.

One should note that throughout the body of literature on speech communication, the terms "speech intelligibility," "speech discrimination," and "articulation testing," are sometimes used interchangeably. "Speech intelligibility" is usually taken to be the generic term associated with most spoken message testing. However, for the present study, operational definitions of speech intelligibility and speech discrimination were adopted. Speech discrimination is defined as the measure of a person's ability to distinguish between different speech sounds or words (Rintelmann, 1979), while speech intelligibility is the person's performance in determining word, phrase, or sentence meaning (Kryter, 1985). In other words, the fact that speech discrimination has occurred does not necessarily mean that the listener has understood the meaning of the spoken message.

In similar vein, several of the ensuing studies discuss the use of "white" noise and "pink" noise. Again, it is not always reported that the strict definitions of these two noise types, as given in ANSI S3.20-1973 (Psychoacoustical Terminology), were applied. White noise is defined as "a noise for which the spectrum density is substantially independent of frequency over a specified frequency range. The slope of the pressure spectrum level of white noise is zero decibels per octave" (ANSI S3.20-1973, p. 59). Pink noise is defined as "a noise for which the spectrum density is inversely related to frequency. The slope of the pressure spectrum level of pink noise is minus 3 decibels per octave" (ANSI S3.20-1973, p. 37).

HPDs and Sound Attenuation

HPDs have historically been available in four basic types which are categorized according to the method of interfacing the HPD to the ear. These include earplugs, ear canal caps, earmuffs, and helmets. Earplugs are inserted directly into the ear canal and are held in place by the pressure of the plug on the canal walls. Semi-inserts (ear canal caps) block the entrance to the ear canal and are held in place by a headband. Earmuffs enclose the entire outer ear (pinna) inside padded cups and are also held in place by a compressive headband. Finally, helmets cover most of the head surface, except for the face, and reduce skull conduction of sound waves.

HPDs vary considerably in their ability to attenuate sound due, in part, to differences in design construction (Edwards, Broderson, Green, and Lempert, 1983). The actual attenuation range is from approximately 3 to 30 dBA (Else, 1973), depending on the particular HPD used. The maximum (theoretical) attenuation that can be provided by an HPD is about 55 dB (Michael, 1965). This limit exists because the bone and tissue sound conduction threshold is about 30 to 55 dB higher than the airborne sound threshold.

The single number estimate of sound attenuation provided by an HPD is indicated by the Noise Reduction Rating (NRR) number which is required on all HPD packages by the Environmental Protection Agency (EPA). The NRR represents the difference between the logarithmic sum of seven C-weighted octave band (125-8000 Hz) "outside" sound levels and the logarithmic sum of the seven A-weighted octave band sound levels under the protector. The measured protector attenuation values are reduced by two standard deviations at each octave band frequency. The C minus A value is then reduced by 3 dB to ensure a conservative estimate (Berger, 1982c). However, this single number reveals little about the differential attenuation of the HPD across the spectrum of frequencies it affects. This information is very important because the frequency-specific attenuation characteristics of an HPD define its protective effectiveness for particular offensive frequencies as well as influence its effect on speech intelligibility performance. It is currently optional for the manufacturer to include a plotted or tabular spectrum of attenuation (in addition to the NRR) on HPD-packaging.

HPD design differences also affect speech intelligibility. For instance, some earplug designs contain a small hole in the body of the plug which allows low-frequency sound (below 1000 Hz) to pass through to the ear. This design feature is incorporated to facilitate speech intelligibility. However, earplugs of this type have been reported to improve speech intelligibility (compared to conventional earplugs) only in noise levels below about 88 dB. For noise levels above 88 dB, speech intelligibility was actually superior for those wearing the conventional earplugs (Michael, 1965).

The tendency of more conventional HPDs to affect speech communication depends on many material and construction factors. For instance, materials of higher density tend to attenuate low frequencies to a greater extent than do loosely-packed materials, such as mineral fiber. If the HPD attenuation is high in the critical speech-bandwidth of approximately 1000-3000 Hz, speech signals will be blocked and speech intelligibility will, of course, be decreased. Several studies have specifically addressed, and arrived at generally agreeable conclusions on, HPD attenuation of sound, while other research has been directed toward the less well-defined effects of HPDs on verbal communication. Two representative studies of the former type are discussed next while a detailed review of the latter body of research appears later.

HPD attenuation characteristics were studied by Abel et al., (1982). The HPDs chosen for the study were the MSA Comfo-500 muff, No-noise hard-hat mounted muff, E-A-R sponge plugs, Willson Sound-Silencer plug, Willson Sound-Ban-Occluder plug, and the Proppo-Plast Swedish wool plug. The findings of this study were that, for the earmuffs, the attenuation characteristics were weak at the lower frequencies (5-15 dB of reduction at 125-500 Hz), but increased in a linear fashion to achieve 20 to 30 dB of attenuation between 2000 and 4000 Hz. Above 4000 Hz, the attenuation value again decreased. On the other hand, the earplugs (E-A-R and Willson Sound-Silencer) provided better low frequency attenuation (15 dB at 125 Hz) with a disproportionately high peak of 35 to 40 dB of attenuation at the frequency band centered at 4000 Hz. Thus, it is quite evident that differences between HPD attenuation characteristics do exist and that these differences dramatically affect the intensity level of sound frequency components entering the ear.

Additional findings were that the amount of attenuation within protector type was generally independent of the subject variables of age and frequency configuration (normal hearing, high frequency loss, and flat loss) of hearing loss. However, there were two exceptions to this finding. For both the E-A-R and the Willson plug, normal hearing subjects achieved the greatest attenuation at a higher frequency (8000 Hz) compared to the 4000 Hz peak for hearing impaired subjects.

Finally, the E-A-R plug and the No-noise muff provided the best overall performance across frequency and subject group. Thus, in general, both plugs and muffs attenuate higher frequencies more than lower frequencies, although the plugs tend to attenuate more of the lower frequencies while the muffs may have an advantage at the higher frequencies. Moreover, these differences in attenuation characteristics will affect speech intelligibility when conflicts arise due to competing speech signal and noise energy at a given frequency, or when certain noise frequencies are at an intensity which effectively masks the important frequency components of the speech signal.

Research conducted by Casali, Lam, and Epps (1985) also evaluated HPD attenuation characteristics along with the effects of user instruction using earplugs, earmuffs, and earcaps. The earplugs used included Flents wax cotton, rubber Willson EP-100, E-A-R foam, wool mineral fiber Bilsom POP, and plastic Tasco RD-1. The earmuffs included E-A-R model 1000, Siebe-Norton Industrial model 4540, Peltor H6A/V, and Willson 365A Sound Barrier. The two earcaps used were Willson 20 Sound-Ban and Flents 055 Peace & Quiet Headband. Subjects donned the HPDs after receiving one of five levels of instruction describing the proper placement and wearing of the devices. In this way, the effect of instruction on achieved attenuation could be assessed.

The attenuation tests were conducted using the Real-Ear Attenuation at Threshold (REAT) method. Sound stimuli were presented using a loudspeaker system in a near-anechoic environment. In the REAT testing procedure, a subject's hearing threshold is assessed at seven or more test frequencies both with and without an HPD. The difference between the occluded and the unoccluded conditions is taken as the amount of attenuation provided by the HPD at that frequency (Berger, 1984). The Casali et al., (1985) testing was conducted in accordance with ANSI Standard Z24.22-1957 in which pure-tone (dBA) occluded/ unoccluded threshold differences were assessed at seven frequencies (125, 250, 500, 1000, 2000, 4000, and 8000 Hz) in an anechoic field.

The HPD attenuation results showed that, as a group, earmuffs provided better sound attenuation at the higher frequencies while the earplugs prevailed at the lowest frequencies. One anomaly appeared with the Willson muff, in which the attenuation characteristics were similar to the earplugs at low frequencies. Also, the differential effects of insertion-instruction levels were especially dramatic for the earplugs. For instance, the amount of attenuation provided by the earplugs was at least doubled when insertion procedures were modeled (face-to-face) compared to a no instruction condition. On the other hand, earmuff/earcap attenuation was not nearly as affected by differences in application instructions, with <u>any</u> type of instructions providing significant improvement over no instruction at all. In the case of all types of HPDs tested, the complete <u>lack of</u> instruction was clearly contraindicated if reasonable attenuation levels were to be realized. Thus, the use of well-designed application instruction is another factor which could indirectly affect speech intelligibility due to changes in the amount of attenuation afforded by HPDs.

Thus, the results of these two studies demonstrate that, in general, earmuffs tend to provide greater attenuation at higher frequencies while earplugs provide better low frequency attenuation. In terms of speech intelligibility, these differences must be taken into account when selecting an HPD for a given noise problem if optimizing verbal communication without sacrificing adequate hearing protection is important. For instance, high attenuation in the critical speech bandwidth of approximately 1000-3000 Hz may be particularly detrimental to the understanding of voice. Though it is important to consider individual HPD differences, on the whole, earmuffs may tend to have higher attenuation in this range.

HPDs and impulse noise. One type of noise environment which adversely affects speech intelligibility is that of high intensity impulse noise. For example, in the vicinity of explosives and ordnance weapons, short duration peak impulsive noise levels of 185 dB may occur (Ward, 1981). Likewise, high impulse noises are common in industry, such as those produced by large hammer forges, presses, and stamping machines, creating the need for HPDs with high attenuation characteristics. Of course, the higher the noise attenuation, the greater the reduction in speech or signal level as well.

Coles and Rice (1965b) compared the pure-tone and speech attenuation characteristics for V-51R and Selectone-K earplugs under long (approximately reverberant temporal conditions) durations of impulse noise. The Selectone-K earplug, unlike the V-51R, is a low pass filter-type plug designed specifically for high-level impulse sounds.

The impulse noise was produced by blank cartridge small-arms firing in a reverberant enclosure. Speech intelligibility was measured using a 50% correct speech reception threshold (SRT) for monosyllabic phonetically-balanced (PB) word lists presented via the playback of a recording of a male voice.

The results of this study showed that the V-51R provided better protection, as evidenced by reduced TTS, from reverberant impulse noise, but that the Selectone-K proved better for speech intelligibility. The apparent problem with the Selectone-K in terms of reduced hearing protection is that the low pass filtering allows too much low frequency/high intensity sound to enter the ear, which contributes to TTS at higher frequencies. Consequently, the intelligibility advantage offered by the Selectone-K earplug is contrasted with its inadequate protection from long-duration (reverberant) impulse noise. Moreover, since industrial impulse noises are most often produced in semi-reverberant, rather than near free-field, conditions (Acton, 1967b), the use of the Selectone-K would be inappropriate in many industrial settings.

The implication of this study, with respect to speech intelligibility, is that in environments with reverberant impulse noises there exists a trade-off predicament between hearing protection and speech intelligibility when using low-pass filter type earplugs. Specifically, in the case of the Selectone-K earplugs, the sufficient attenuation provided at the higher frequencies is offset by inadequate attenuation of low frequency sounds, resulting in low frequency-induced TTS. On the other hand, an increase in speech intelligibility is attainable with this type of earplug and a long-duration, impulse noise condition, as demonstrated by this study.

Several characteristics of ambient noise conditions have been investigated as to their effect on speech communication, some in combination with HPD use. A brief review of those studies which are pertinent to the HPD-communication issue follows.

Effects of Ambient Noise Intensity Level

Effects of high background noise levels. The masking effect of noise on speech is approximately linear for noise levels ranging from 50 to 90 dB (Hawkins and Stevens, 1950). In addition, speech intelligibility is reduced in the presence of noise both at normal levels (approximately 45 to 75 dBA according to Kryter, 1984) and high levels (above 100 dB according to Pollack and Pickett, 1957) of speech. Noise in excess of 55 dB for tones of 1000 and 2000 Hz, and 8 dB for 100 Hz can cause distortion within the cochlea (Lawrence and Yantis, 1956). This distortion is known to increase with rising noise levels as evidenced by the data of Martin, Howell, and Lower (1976). They found that increasing the ambient level from 65 to 95 dB resulted in a decrease in speech intelligibility. This finding occurred regardless of signal-to-noise (S/N) ratio (-5, 0, 5, and 10 dB) or utilization of HPDs. (A S/N ratio of, for example, 5 dB means that the level of the signal exceeds the level of the noise by 5 dB, and similarly, a S/N ratio of -5 dB indicates that the signal is exceeded by the noise in the amount of 5 dB). The added effect of the HPD, when used, reduces the sound level entering the ear, and hence, decreases the cochlear distortion, so that speech intelligibility is restored.

In response to the potentially detrimental effects of intense sound (above approximately 80 dB), the ear (i.e., middle ear) contains a protective mechanism known as the Intra-Aural Reflex. The mechanism is comprised of a set of muscles (tensor tympari and stapedius) which in reflexive response to loud sounds contract in opposing directions pulling on the malleus and stapes bones, thereby "stiffening" the chain of ossicular bones. The effect of this reaction is an initial reduction in the transmission/amplification characteristics of the ear to external sounds. (Partial adaptation occurs after approximately 15 minutes of constant exposure.) It should be noted, however, that the reaction time of the reflex is at least 10 msec and is therefore ineffective against impulse/explosive sound signals (Ward, 1986).

Effects of low speech and noise levels. With low level speech sounds, high frequency/low energy consonant sounds which are important for determination of word structure (Lindeman, 1976) can be diminished, resulting in a decrease in speech intelligibility (Acton, 1967a). Howell and Martin (1975) demonstrated this effect in a study in which a reduction in speech intelligibility occurred when subjects wore HPDs in noise levels of 65 dBA or below. However, since ear protection is seldom used in noise levels below 80-90 dB (Acton, 1967a), this problem should rarely occur in practice.

Ambient Noise Spectral Characteristics

In addition to overall decibel level, industrial noises vary greatly in their intensity spectra. These different sound intensity-by-frequency profiles are an important factor since they interact with HPD attenuation profiles in their influence on speech perception. This was evidenced in an Abel, Alberti, Haythornthwaite, and Riko (1981) study in which crowd noise (85 dBA) was shown to be a more effective masker of speech than was white noise (85 dBA) in the occluded condition. In addition, the Howell et al., (1975) study revealed this differential effect in comparing two noise types (designated "A" and "B") for their effect on speech intelligibility. The masking noise spectra for both the A and B noises were such that their main energy ranges fell within the frequency range of typical male speech. However, the spectra were differently skewed (mode for A at 1000-2000 Hz and for B at 63-250 Hz) and symmetrical (with respect to each other) within the frequency range of 31.5 Hz to 16,000 Hz. Their study showed that while one noise type (B) resulted in superior speech intelligibility at a high S/N ratio (10 dB), the other noise type (A) resulted in better intelligibility scores at a low S/N ratio (-5 dB). The differences were not statistically different however. In any case, this study hinted that the relative effectiveness of speech intelligibility in noise is, in part at least, a function of the broadband noise spectral characteristics.

Wide differences in industrial noise spectra are illustrated by a comparison of typical industrial noises such as those recorded in a survey conducted in the Casali et al., (1985) study. An example was the noise emitted from a machine shop used in an electric motor manufacturing process. The 1/3 octave band (OB) noise spectra yielded a sound pressure level (SPL) variation of only 10 dB across the frequencies centered at 125, 250, 500, 1000, 2000, 4000, and 8000 Hz. On the other hand, the sound spectra of a pedestal grinder in the same plant showed an SPL variation of 35 dB from 125 Hz to 8000 Hz. It is quite clear that industrial noises vary considerably in their sound spectral characteristics, contributing an important basis for appropriate HPD selection.

Signal-to-Noise (S/N) Ratio

The optimal (in terms of speech perception) S/N ratio for normal hearing individuals is a signal level of 70 dB in a background noise level of 60 dB, or a ratio of 10 dB (Lindeman, 1971). Moreover, in order to maintain a specified level of speech intelligibility over the typically encountered speech intensity range of 40-100 dB, the established S/N ratio must be sustained (Tempest, 1985). However, many factors, such as HPD attenuation characteristics, noise type, degree of hearing loss, speech material used (e.g., sentences versus isolated words), and overall sound levels (noise and speech), have varied effects on speech intelligibility at a given S/N ratio. In general, though, increasing the S/N ratio is the single most effective method for avoiding the masking effects of noise (Kryter, 1985), and thereby optimizing the conditions for speech intelligibility.

Lombard "noise compensation" reflex. In some industrial settings, noise levels that vary over time may have an adverse effect on speech intelligibility. Martin et al., (1976) found that regardless of HPD usage, a person's speech level will increase as noise levels increase. This phenomenon occurs as result of the Lombard, voice reflex, or noise compensation principle, in which the speaker compensates for the changing level of background noise. According to Lane and Tranel (1971), the "reflex" is actually a conditioned or learned response in which the speaker attempts to maintain speech intelligibility (constant ratio) in changing noise levels. However, the voice-to-noise ratio which starts out at less than 1 to 1, actually decreases as noise level increases (Acton, 1977). The ratio of the overall rate is approximately equal to a 5 dB increase in speech for every 10 dB increase in noise level (Martin et al., 1976). Thus, a progressive reduction in uttered speech-to-noise ratio, as well as in speech intelligibility, occurs as the level of background noise increases.

Lombard "occlusion" reflex. Another characteristic of the Lombard effect was noticed by Kryter (1946) when he found that the use of earplugs (V51-R) in noise (75 dB and higher) resulted in a reduction of the wearer's spoken voice level by about 1-2 dB. Martin et al., (1976) concluded that the average drop in voice level (from their experiments) was about 2-3 dB for either plugs (V-51R) or muffs (Amplivox Sonogard, fluid-filled seals). The explanation given for this reflex action (Kryter, 1946) is that of a compensation response to the feedback level of the speaker's own voice. In noise, one's own voice sounds louder to oneself when wearing an HPD, than the voice level fed back through the ear alone. The reason for this difference is that the speaker's own voice feedback is aided by bone conduction with the HPD donned, in addition to the reduction in the air-conducted noise level. HPD usage in quiet (e.g., 25 dBA ambient noise) however, results in an increase in the user's voice level when compared to an unoccluded condition (Casali, Horylev, and Grenell, 1987).

The HPD-enhanced bone conduction occurs at frequencies below 2 kHz relative to the unoccluded ear (Bekesy, 1960). The magnitude of the effect is strongest when the ear canal is sealed at the entrance (e.g., earcaps) and decreases when either earmuffs (large internal volume) or earplugs (minimal internal volume between plug and tympanic membrane) are donned (Berger, 1986). The "occlusion effect" can be as great as 25 dB at 500 Hz, although it is also highly variable among individuals (Rintelmann, 1979). In terms of speech communication, the reflexive voice level reduction occurring for HPD users in noise results in a decrease in speech intelligibility for the listener (Martin et al., 1976).

To overcome the occlusion reflex problem, it has been suggested (Burns, 1973) that workers be advised to speak loudly when communicating while wearing HPDs. In this vein, it has been estimated (Acton, 1967a) that shouting could increase vocal output by about 10 dB and that an additional 6 dB of noise could be tolerated by halving the voice to ear distance (Webster, 1965). Unfortunately, as pointed out by Pickett (1956) and Acton (1970), while these alternatives would be useful for lower noise levels, at higher noise levels, the best expectation would be that of very limited compensation. Furthermore, due to the occlusion reflex, speakers wearing HPDs tend to talk softer, rather than louder. Therefore, they would have to continuously make a conscious and unnatural effort to speak at intensity levels which would appear abnormally high in reference to the "internal" feedback about their own voice level. Training workers to accomplish such a task may prove to be very difficult, if not impossible.

Effects of speech level on voice quality. Voice "quality" is sometimes used to refer to the spectral characteristics of the speaker's voice pattern and is a factor which may affect speech intelligibility. Martin et al., (1976) analyzed the voice spectra recorded for talkers presenting word lists under three hearing configurations (unoccluded, earplug-occluded (V51-R), and earmuff-occluded (Welsh 4530)) for each of four noise levels (67, 77, 87, and 95 dBA). During the experiment, one of four subjects presented word lists (Boothroyd's isophonemic words--1968) to the other three, while each listener was under one of three different hearing configurations. Each subject participated as both talker and listener. Talkers were given no instruction as to the needed voice level. The voice spectra for all four subjects were averaged for each hearing configuration and noise level. The results showed that for any given noise level, no substantial differences in voice spectra occurred between the three hearing configurations, other than the expected differences in voice level associated with the occlusion reflex.

Moreover, an additional experiment (within the same study) was conducted to determine if the enhanced low frequencies produced by earplug usage (occlusion effect) would result in a subtle alteration of the talker's voice spectrum with a subsequent effect on speech intelligibility for the listener. The results showed no overall significant difference in speech intelligibility (articulation scores) for the listeners due to earplug-induced changes in the talkers' voice quality (compared to an unoccluded condition).

In another study (Webster and Klumpp, 1962), significant changes in voice quality resulted from forcing an increase in the intensity of the speaker's voice level. The change in vocal output was accomplished by raising the ambient noise level either via a noise generator or by increasing the number of persons talking in a group. As the force of vocal effort increased, the spectral pattern shifted with an increase in higher frequency output. Since moderately high frequency components in the range of 1600-1700 Hz are critical to effective speech intelligibility (Kryter, 1960), one would expect an increase in speech intelligibility with higher vocal efforts. However, it has been shown (Pickett, 1956) that increasing vocal effort from a level of 55 dB to 78 dB in noise under free field conditions, resulted in no increase in speech intelligibility, with further increases in vocal effort (louder shouting) resulting in rapidly deteriorating performances. This finding was true with fixed S/N ratio as well as with increasing S/N ratios (-6, 0, and 6 dB).

On the other hand, in a study by Dreher and O'Neill (1957), the S/N ratio of the message being delivered was held constant via an automatic volume control system, and the differences in speech intelligibility between quiet and noise conditions appeared to be due to changes in the speaker's voice spectrum, not overall voice level. Consequently, differences in voice quality, as well as voice level, can affect speech intelligibility.

In addition to the aforementioned ambient noise characteristics, use of HPDs, forced vocal effort, and voice spectral quality factors, another important consideration in speech intelligibility testing is the hearing level of the subject pool. Prior studies addressing this factor are reviewed next.

Research on Speech Intelligibility with Normal Hearing Subjects

Although workers' complaints of HPD communication interferences have been frequently noted, research has not unconditionally supported this claim. Subjects with normal hearing, as established through audiometric testing, have not generally demonstrated a loss in speech intelligibility when wearing an HPD and communicating in environments containing high (above 80 dB) noise levels.

One of the earliest studies investigating the effects of HPDs on speech intelligibility in noise was conducted by Kryter in 1946. Eight college-aged men with normal hearing listened to monosyllabic, phonetically-balanced (PB) type word lists in an industrial/military noise setting using a public-address system, a reverberation chamber, and electronically-generated engine noise. The noise levels presented ranged from ambient room noise (less than 65 dB) to 115 dB in 10 dB increments. The S/N ratio was varied from -5 to 15 dB in 5 dB increments. Speech intelligibility was measured by the percentage of words correctly understood.

Kryter's study found that normal hearing subjects (V-51R Ear Wardens) perceived the monosyllables in noise levels of 80 dB and above with no adverse effects on speech intelligibility due to the earplugs. This performance was maintained with S/N ratios ranging from -5 to 15 dB. In addition, the use of earplugs in noise above 80 dB actually facilitated speech intelligibility by 10% compared to the unoccluded condition. However, for noise levels below 80 dB, the use of earplugs degraded speech intelligibility regardless of S/N ratio.

Pollack (1957) also studied speech intelligibility for normal hearing subjects wearing earplugs in an ambient noise condition. In this study, however, the noise condition was presented directly into the ear via earphones. Five "listeners" were exposed to electronically-generated noise at intensity levels ranging from 70 to 130 dB. The subjects' task was to detect monosyllabic word lists presented at S/N ratios of 0 and 12 dB, both with and without the aid of V-51R earplugs (under the earphones). The measure of speech intelligibility was the percentage of words correctly detected. The results showed that for the occluded versus the unoccluded condition, little differences in speech intelligibility were obtained for noise levels up to 110 dB. However, the HPD provided superior performance for the higher remaining noise levels (110-130 dB) at both S/N ratios.

Another aspect of the Pollack study involved exposing both unoccluded and occluded subjects to a fixed noise level of 130 dB for successive 100-second trials. The HPD used for this experiment was a wax-impregnated cotton earplug. Speech signals were presented through earphones worn over the earplugs. This experiment demonstrated that in a very high level noise condition, the use of the HPD resulted in superior speech intelligibility compared to the unoccluded condition. Moreover, the steady, cumulative decline in speech intelligibility (i.e., speech intelligibility decreased with continued sound exposure over time, perhaps due to TTS) which occurred under both occluded and unoccluded conditions, was greatly reduced with the use of the HPD.

Frohlich (1969) tested subjects with normal hearing for speech intelligibility using three HPDs in a background of aircraft noise. Twenty-five young males with normal hearing listened to multiple series of 10 German double-digits in a background noise of 104 dB. The digits were presented with average speech levels of 93, 88, and 83 dB to subjects wearing the Selectone-K earplug, Com-fit earplug (Super-Sonex), Willson Sound-Barrier earmuff, or no HPD. Speech intelligibility was measured using average articulation scores. An improvement in speech intelligibility occurred with the Willson earmuff (highest articulation score) as well as with the Com-fit earplug. However, the Selectone-K was concluded to be inappropriate (lowest score) for speech communication in aircraft noise environments. Also, the effect of decreasing S/N ratios was, as expected, a decrease in speech intelligibility.

Speech reception for normal hearing subjects using person-to-person (rather than recorded or loudspeaker-presented) communication was investigated by Williams, Forstall, and Parsons (1971). Nine adult subjects with normal hearing were exposed to recorded aircraft engine noise, both with and without V-51R earplugs, while in a soundproof testing room. Subjects listened to word lists of the Modified Rhyme test delivered by a talker (wearing earplugs) at a distance of about 83.82 cm (33 in). Subjects were told to keep their eyes on their response sheets to avoid visual cueing. Speech intelligibility was measured by percent correct responses of the difference score between the occluded and unoccluded conditions. The results showed a significant improvement in speech intelligibility when using the HPD in the noise condition (compared to the unoccluded condition).

Martin et al., (1976) also investigated the effects of HPDs on subjects' speech intelligibility in noise. In their experiment, 12 male college students with normal hearing listened to recorded lists of isophonemic words published by Boothroyd (1968). The testing was performed in a semi-reverberant room (reverberation time of 0.73 s at 500 Hz) under two electronically-generated noise conditions (designated "A" and "B" as previously discussed) with S/N ratios of -5, 0, 5, and 10 dB. The HPDs used were the Ear Wardens V-51R earplug and the Welsh 4530 earmuff. For the measure of speech intelligibility, each of the written response lists was scored for the percentage of correctly recorded phonemes (3 phonemes per word), out of a possible total of 30 phonemes per list. The results indicated that for noise levels between 65 and 80 dB, no significant differences were found between the occluded and the unoccluded conditions. This finding was true regardless of noise type or S/N ratio. A comparison of mean discrimination scores between noise types as a function of noise level (S/N ratios averaged) yielded the following results: for the A (higher frequency) noise at 80 dB, the use of earplugs resulted in significantly better discrimination scores when compared to the unoccluded condition; for the B (lower frequency) noise at 80 and 95 dB, using earplugs resulted in better discrimination scores than those achieved in the unoccluded condition. Also, for the B noise at 95 dB, the use of earplugs resulted in a significant improvement in word discrimination when compared to the use of the earmuffs. There were no significant differences between noise types with respect to intelligibility.

Abel, Alberti, and Riko (1980) studied speech intelligibility for normal hearing subjects in noise using a MSA Comfo-500 earmuff. Twelve subjects (audiometrically-tested for normal hearing), aged 35 to 50, listened to 12 lists of 25 monosyllabic-PB words presented by recorded voice. Speech levels were presented at 80 and 90 dBA in the presence of white noise (85 dBA), crowd noise (85 dBA), or a quiet ambient condition. The taped speech was presented through a single loudspeaker, centered in front of the subject, while the noise was presented through two additional loudspeakers mounted on the side walls. This arrangement formed a "T" pattern in a soundproof booth with the subject located at the intersection. Speech intelligibility was measured as a percentage of correctly reported words. The major finding was that HPD usage did not enhance nor degrade speech intelligibility when compared to the unoccluded condition, for any combination of ambient noise spectral type and speech level. An additional finding was that speech intelligibility was significantly better in the quiet condition than in the noise (white or crowd noise) background conditions, regardless of hearing configuration, with crowd noise exhibiting the strongest masking effects. In addition, the lower speech level (80 dBA) resulted in a significant decrease in speech intelligibility regardless of hearing configuration or spectral noise type (white or crowd noise at 85 dBA) when compared to the higher speech level (90 dBA).

Normal hearing subjects were again tested by Abel et al., (1982). This study was similar to the 1980 study, except that the E-A-R plug and the Willson Sound-Silencer plug were used in addition to the MSA Comfo-500 muff for the occluded condition. Another difference was that speech intelligibility was measured as a difference score between the occluded and the unoccluded condition for each subject, due to significant baseline hearing differences among subjects in the unoccluded condition. Again, the background noises included white and crowd noise (both at 85 dBA) and a quiet condition. The results of this study paralleled the authors' earlier study (1980) in that for normal hearing subjects, the use of HPDs in noise had no effect on speech intelligibility when compared to the unoccluded condition. Also, no differences were found between the intelligibility effects of the earmuff and the earplug for either background environment (quiet and noise) or for level of S/N ratio used (-5 and 5 dB).

Normal hearing summary. As evidenced by the prior discussion, for subjects with normal hearing, the effects of HPDs on speech intelligibility in the presence of noise levels above 80 dB is, in general, to enhance or at least maintain (as noise level increases) intelligibility for the listener. For noise levels below 80 dB, however, the use of HPDs can interfere with speech intelligibility. However, in view of the fact that some frequencies of sound may be harmful to hearing at levels even below 80 dB, the use of HPDs solely for hearing protection reasons (effects on intelligibility notwithstanding) may be necessary.

Types of Hearing Loss

It is common knowledge that exposure to intense sound can result in either temporary or permanent hearing loss (Henderson, Hamernik, Dosanjh, and Mills, 1976). A frequent cause of hearing loss is industrial noise (Ruedi and Furrer, 1946), and it is reported (Cheremisinoff et al., 1978) that at least 10% of all industrial workers are known to have some type of loss. Moreover, concern has been expressed (Rintelmann, 1979) over the potential increase of noise-induced hearing loss in industry, even in the face of noise abatement efforts.

Temporary threshold shift. Excessive noise exposure (typically above 80 dB) can cause auditory fatigue which is manifested as a change in absolute auditory sensitivity. This change, which was mentioned earlier as TTS, is subjectively characterized by the unusual quiet that is perceived by the victim after exposure to intense sound. The frequency at which the maximum threshold shift occurs is related to the frequency of the sound stimulus, but typically it is approximately half an octave above the stimulus (Tempest, 1985). While TTS results in immediate hearing loss, it is reversible with recovery time depending on a host of factors including noise characteristics, exposure time, and individual differences (Salvi, 1976).

Permanent threshold shift. The more severe form of hearing loss which results in a permanent threshold shift, continues to increase with prolonged or repeated exposures to high noise levels. Noise-induced permanent threshold shift (NIPTS) is almost always greatest at 4 kHz, which in time expands to include frequencies above and below that frequency (Cheremisinoff et al., 1978). While the exact relationship between TTS and PTS is unclear, Robinson (1976) reports that there is strong evidence that being very susceptible to TTS increases one's susceptibility toward PTS.

Presbycusis. A third form of hearing loss, which is the most common type, is called "presbycusis," or hearing loss due to aging (Tempest, 1985). Presbycusis is similar to NIPTS in that it has an insidious onset and it usually affects the higher frequencies. However, presbycusis effects differ from those of NIPTS in that aging effects typically begin at the highest audible frequencies (20,000 Hz) and then progressively spread to the lower frequencies (Sataloff, Sataloff, and Vassallo, 1980). By about 50 years of age, the deterioration has often progressed to include frequencies below 8000

Hz. At this stage of presbycusis, the victim experiences increased difficulty in understanding spoken utterances as opposed to difficulty in general (nonverbal) hearing. Initially, the intelligibility loss is greatest when several people are talking at once (e.g., a cocktail party effect), or with high-pitched female voices. However, as the hearing loss progresses even further (affecting 1000-3000 Hz), discrimination becomes similar to those individuals with severe noise-induced hearing loss, in which the ability to distinguish between words with the same high-frequency consonants (e.g., "jet," "get," "yet," or "yes") becomes difficult under any condition (Sataloff et al., 1980).

The hearing of speech is considered to be reasonably well-represented by audiometric threshold testing of pure tones at frequencies of 500, 1000, 2000, and 3000 Hz (Bergman, 1980). However, good hearing ability at higher frequencies of 4000-7000 Hz has been shown to contribute to improved speech reception and intelligibility (Bergman, 1980). In addition, a study by the same author comparing young (aged 20-29) and old (aged 60-69) subjects with normal hearing demonstrated that for the older group, low-pass filtering at 2 kHz differentially reduced their speech intelligibility performance. Thus for older persons, the higher frequency (above 2 kHz) components of the speech message are especially critical to speech intelligibility performance.

Research on Subjects with Non-Uniform Noise-Induced Hearing Loss

Coles and Rice (1965a) studied the effects of HPD attenuation on speech intelligiblity in noise for subjects with noise-induced hearing loss (NIHL). Subject groups with either severe high-tone loss, moderate high-tone loss, or normal hearing listened to monosyllabic-PB word lists in a quiet and noise (level unspecified) background. The HPD used was the Selectone-K earplug, a low-pass filter plug emphasizing high frequency attenuation. In the quiet condition, NIHL subjects (who had intelligibility impairments without protection) experienced additional reductions in speech discrimination when wearing the HPD. This was true even when optimal sound conditions were produced via signal amplification. However, for the noise condition, those subjects demonstrating a pre-existing loss in speech discrimination in the unoccluded condition experienced no change in speech intelligibility while wearing the HPD.

Frohlich (1969), in his previously-mentioned study, also investigated subjects with high frequency loss for speech intelligibility in noise both with and without HPDs. The subjects were 10 senior aviators with bilateral, high frequency hearing loss above 2 kHz. Test conditions were the same as for normal hearing subjects with a background aircraft engine noise level of 104 dB and averaged speech levels of 93, 88, and 83 dB. The results showed a much lower speech intelligibility score for the hearing loss subjects in both the occluded and unoccluded conditions when compared to normals. This effect was even more pronounced as S/N ratios decreased from -11 to -21 dB. Also, within the hearing loss group, the occluded condition resulted in much lower intelligibility scores when compared to the unoccluded condition.

Acton (1970) tested 27 industrial workers with NIHL of varying degrees for speech intelligibility in noise without HPDs. Speech intelligibility was measured using monosyllabic-PB word lists constructed from 100 phonemes and presented under six S/N ratios of -5, 0, 5, 10, 15, and 20 dB. Subjects were audiometrically-tested for bilateral, pure-tone losses (frequency range of 250 to 10,000 Hz) and divided into 3 groups based on the lowest S/N ratio at which a discriminatory response was given. Testing was conducted in a semi-reverberant room in which signal and noise were produced from three loudspeakers arranged in a "T" pattern. The subjects were positioned at the "T" pattern intersection with the signal source positioned in front of them, while a loudspeaker mounted on each side wall produced the background noise. Pink noise was presented at 60 dBA to simulate industrial noise. Speech intelligibility was measured as percent correct recognition. Acton found that for above moderate pure-tone hearing losses, speech intelligibility was inversely related to hearing loss. The study clearly demonstrated that speech intelligibility is degraded for non-wearers of HPDs who have a hearing impairment.

Similar to Acton (1970), Kuzniarz (1973) studied hearing loss and speech intelligibility in noise without HPDs. Thirty subjects, aged

25-40 with NIHL (audiometrically-tested), were tested for speech intelligibility in a semi-reverberant room in quiet and in low frequency noise. Another 30 subjects with normal hearing were used as controls. Speech intensity level was constant at 70 dB with S/N ratios ranging from 15 to -15 dB in 5 dB step increments. The results demonstrated that all subjects with NIHL were adversely affected (reduced speech intelligibility) by the low frequency noise at S/N ratios of 5 and 10 dB. In addition, the loss of intelligibility, was found to involve speech band frequencies above 2000 Hz. In other words, frequency bands above 2000 Hz were demonstrated as important for speech intelligibility. As suggested by this study, it appears that the masking of low frequency sounds especially hinders speech intelligibility for subjects with NIHL. An explanation for this phenomenon may be that since the low frequencies are masked by noise and the higher frequencies by NIHL, an acoustic environment is created in which the subjects are left essentially deaf.

The effects of noise-induced hearing loss on speech intelligibility has also been studied by Lindeman (1976). Hearing loss was measured at three frequencies (2500, 3150, and 4000 Hz) which the author considered the most relevant to speech (based on earlier work). Subjects (537 total) with NIHL listened to 20 monosyllables (per test) at 90 dB via a loudspeaker both with and without earmuffs. The noise condition consisted of white noise presented by two additional loudspeakers at a sound pressure level of 80 dB. Speech intelligibility was measured by percentage of correct responses. The major finding of this study was that while slight pure-tone hearing loss did not interfere with speech intelligibility for the occluded condition, as the degree of hearing loss increased, speech intelligibility in the occluded condition decreased when compared to the unoccluded condition.

Lindeman's (1976) finding that speech intelligibility is hindered by HPDs in noise for the hearing-impaired was not supported in a study by Rink (1979). Four groups consisting of normal hearing, presbycusis loss, NIHL loss, and sensori-neural loss (cause unknown) defined the subjects used in this study. The measure of speech intelligibility was percentage of correct responses using 50-word presentations of the Modified Rhyme test, evaluated in both quiet and noise (90 dBA) conditions. The speech levels in quiet and noise were 65 and 85 dBA respectively. The HPD used for the protected condition was the Willson Sound-Barrier earmuff. The results for normal hearers were that speech intelligibility was unaffected by HPDs in quiet, while a gain in speech intelligibility was demonstrated for the HPD condition in noise (90 dBA). In contrast, for all three hearing-impaired groups, the HPD adversely affected speech intelligibility in quiet (compared to an unoccluded condition), but had no effect in the noise condition.

The Rink (1979) study supports the findings obtained in the Coles et al., (1965a) study in that it failed to demonstrate any change in speech intelligibility in noise for those individuals with hearing loss while in an occluded condition (compared to an unoccluded condition).

However, there was also no difference in intelligibility performances for either normals or sensori-neural groups in the presence of noise while in the unoccluded condition. Consequently, Rink's findings suggest that when hearing impairment is not severe enough to interfere with intelligibility in noise (unoccluded condition), the additional impairment introduced by the HPD is not enough to produce a degradation in speech intelligibility.

The previously mentioned, Abel et al., (1980) study evaluated speech intelligibility for subjects with bilateral, high frequency loss while wearing an HPD in a noise environment. Noise-induced high frequency hearing loss was determined by audiometric-testing. Subjects had 5 to 25 dB losses at 500 Hz and sloping losses of 35 to 65 dB between 500 and 4000 Hz. The subjects were divided into two age groups of 35-50 and 51-65 years old. The HPD used was the MSA Comfo-500 earmuff. For all three background conditions (quiet, 85 dBA white noise, or 85 dBA crowd noise), speech intelligibility was significantly decreased in the occluded condition (compared to the unoccluded condition) for both age groups. (Recall that Rink (1979) and Coles et al., (1965a) found no change for NIHL subjects' intelligibility scores with HPDs in noise.) The greatest reduction in intelligibility scores (due to HPDs) occurred in the quiet background condition which was in agreement with Rink (1979) and Coles et al., (1965a). These findings were true for both S/N ratios (-5 and 5 dB) used.

Subjects with high frequency hearing loss were again studied by Abel et al., (1982), only this time several types of HPDs were used, including the MSA Comfo-500 muff, E-A-R plug, No-Noise muff on helmet, Willson Sound-Silencer plug, Wilson Sound-Ban-Occluder plug, and the Proppo-Plast Swedish wool plug. (The methodology for this experiment was previously described.) The results showed that regardless of HPD type, the use of an HPD in all three background conditions used (quiet, and white or taped crowd noise at 85 dBA), at either S/N ratio (-5 and 5 dB), again resulted in a decrease in speech intelligibility for persons with high frequency loss when compared to the unoccluded condition.

NIHL summary. For subjects with a large degree of high frequency hearing loss, the research results generally show that speech intelligibility in noise levels of sufficient intensity (about 80 dB or above) is adversely affected regardless of HPD utilization. The effect of adding hearing protection may result in an additional decrease in speech intelligibility for the hearing-impaired. The common explanation given for this added decrease is that the HPD reduces the speech level below an already abnormally high threshold residing in the higher frequency hearing range (Kryter, 1985). For subjects with a moderate or small degree of hearing loss, the results generally show a lack of degraded speech intelligibility, due to HPD use, at the higher noise levels (about 80 dB or above), suggesting that the hearing impairment must be sufficiently pronounced for the HPD-interference effect to occur.

Research on Subjects with "Flat" (Uniform) Hearing Loss

Individuals with "flat" hearing loss impairments are identified through audiometric testing as exhibiting similar degrees of hearing loss across a wide range of audible frequencies.

Subjects with flat-loss hearing were studied by Abel et al., (1980). Audiometric tests were used to identify bilateral and relatively flat-losses of approximately 30 to 50 dB at 500 Hz and 45 to 65 dB at 4000 Hz. The results showed that the use of a MSA Comfo-500 earmuff (compared with the unoccluded condition) significantly degraded speech intelligibility for all six combinations of speech (80 and 90 dB) and background (quiet, 85 dBA white noise, or 85 dBA crowd noise) conditions. Also, for the occluded condition, a higher S/N ratio (5 dB) resulted in significantly better speech intelligibility in each background condition when compared to a lower ratio (-5 dB). In addition, scores were similar in all three backgrounds at a given S/N ratio while wearing the HPD. Thus, it would seem that for those with flat-loss hearing, the type of background noise is not as important as is S/N ratio for speech intelligibility when wearing an HPD. Comparisons between the flat-loss subjects and those with high frequency loss showed that when using the HPD, flat-loss subjects' intelligibility was inferior in all conditions except for the crowd noise, in which similar scores were obtained. For the unoccluded condition, the only difference between the two groups was in the quiet background at the lower S/N ratio (-5 dB), in which the flat-loss subjects had lower scores.

Subjects with flat-loss were again studied by Abel et al., in 1982. In this study, the E-A-R plug was used in addition to the MSA Comfo-500 muff. The methodology and treatment conditions were the same as those in the above mentioned Abel et al., (1980) study. The results showed that the use of the earplug in quiet, white or crowd noise (85 dBA) severely interfered with speech intelligibility compared with the unoccluded condition. The general conclusion drawn from this study was that for persons with flat hearing loss, HPD usage in quiet or in noise causes a reduction in speech intelligibility.

Flat hearing loss summary. In conclusion, for subjects with flat hearing loss, the effect of HPDs on speech intelligibility in quiet conditions or in ambient noise is to degrade performance, especially at lower S/N ratios (e.g., -5 dB).

Effects of Conditioning

Another factor which has been shown to influence speech intelligibility is that of getting "accustomed" to a background noise. Acton (1970) compared three groups (different degrees of NIHL) of "conditioned" industrial workers against an "inexperienced" control group of university staff for differences in speech intelligibility due to conditioned speech reception/discrimination in noise conditions. The control group subjects were audiometrically screened for normal hearing which was defined as a hearing loss of less than 15 dB at any one of 6 frequencies tested (500, 1000, 2000, 3000, 4000, 6000 Hz). Subjects listened (unoccluded) to phonetically balanced (PB) monosyllabic word lists delivered in pink noise (60 dBA) at progressively smaller S/N ratios. The three NIHL groups were delineated by the lowest S/N ratio at which a response was uttered by the subject (-5, 0, and 5 dB, respectively). The experiment was conducted in a semi-reverberant room which contained two noise loudspeakers and one speech signal loudspeaker arranged in a triangular configuration. The subject was seated on the base of the triangle, equidistant (six ft) from each loudspeaker and facing the speech-signal loudspeaker.

Speech intelligibility was measured as percentage of correctly repeated phonemes. Results showed that the industrial group with the smallest degree of hearing loss produced speech intelligibility scores which were similar to those of the control group and actually better at a S/N of 5 dB. That is, the "conditioned" industrial workers had perhaps learned to compensate in noise conditions and maintain speech intelligibility. The two remaining NIHL groups diverged from the control group in a manner consistent with their hearing loss spectral profiles (measured via pure-tone audiograms).

It should be noted, however, that the conditioning effect should not be construed as a justification for not wearing HPDs in noise, because continued exposure to noise would eventually result in degraded hearing.

Effects of Visual Cueing

Visual cueing, resulting from observation of a speaker's facial and lip movements, has been shown to increase speech intelligibility as background noise increases. Martin et al., (1976) found that as noise levels increased up to 80 dBA, visual cueing enhanced speech intelligibility for subjects with normal hearing, and that, above 80 dBA, visual cueing proved more effective than did the use of HPDs in maximizing speech intelligibility. For instance, at an ambient noise level of 95 dBA, an increase of 30% in intelligibility scores occurred when using visual cueing, in both occluded and unoccluded conditions. Interestingly, this improvement is equivalent to that obtained with a reduction of background noise levels by approximately 10 dB. In addition, visual cues have also been shown (Rink, 1979) to increase speech intelligibility for subjects with sensori-neural hearing loss.

In general, however, the benefit of visual cueing is limited by the opportunity for face-to-face communication at the work-site and its presence should not be assumed as a precondition for predicting speech intelligibility in most practical situations.

Effects of Language Fluency

Another important factor in speech intelligibility is the person's fluency level with the dominant language spoken in the industrial setting. If lack of language fluency interferes with comprehension, then speech intelligibility could be further compounded by additional factors such as hearing loss or HPD usage.

Abel et al., (1981) also studied the effects of fluency on speech intelligibility for normal hearing subjects (aged 35-50) in noise, both with and without HPDs. Non-fluency was defined (by the authors) in an example as "English spoken ungrammatically, difficulty in finding appropriate words but able to converse and to understand instructions adequately" (Abel et al., 1981, p. 709). Again the HPDs used were the Comfo-500 earmuff, E-A-R plug, and the Willson Sound-Silencer. Speech intelligibility was measured as the percentage of words (monosyllables) correctly repeated.

The results demonstrated that non-fluency significantly decreases speech intelligibility in background conditions of quiet, white, and crowd noise with speech levels of 80 and 90 dB against an 85 dB noise level. In comparison to fluent subjects with normal hearing, the average intelligibility scores for non-fluent subjects were approximately 10 to 15% lower under any combination of noise type and speech level. Also, no differences were found between the occluded and unoccluded conditions under any combination of background noise and S/N ratio. Thus, the lack of adequate language fluency impedes speech intelligibility and has a relatively constant effect, irrespective of other factors.

Detection of Warning Signals

Perception of warning signals (buzzers, bells, etc.) is a related matter important for consideration since its interference by HPDs could result in disastrous consequences.

The effect of HPDs on the perception of warning signals in noise was studied by Wilkins and Martin (1982). Several experiments were conducted using an anechoic room with the signal and noise presented using a single loudspeaker. Sixteen subjects with normal hearing (audiometrically-tested) listened to signals (warnings) in the presence of noise at 75 and 95 dBC with and without HPDs. Warning sounds included a wailing siren, bell, two-tone signal, high-tone signal and a low-tone signal. The general finding of this study was that HPDs had no adverse effects on the perception of warning sounds unless those sounds were already somewhat inaudible under the unoccluded condition.

For workers with NIHL, the use of HPDs has been reported (Wilkins and Acton, 1982) to increase the risk of job injury due to difficulties in hearing auditory warnings. To aid signal perception, Wilkins and Martin (1982) have suggested wearing HPDs with adequate (versus maximum) protection and increasing warning signals 15 to 25 dB above the masking threshold.

Literature Conclusions

Discriminations of spoken utterances, as suggested by the preceding literature review, are influenced by many factors, including HPD attenuation characteristics, ambient noise levels, ambient noise spectral characteristics, S/N ratio, and listeners' degree of hearing loss among others.

The practicality of these findings is that for a given noise environment, the overall noise sound pressure level and the specific frequency components need to be at a sufficient intensity to warrant the use of HPDs. If a high noise level environment merits the use of an HPD, then there is the additional problem of selecting an appropriate HPD for the particular noise (spectrum) condition. As pointed out earlier, the use of an inappropriate HPD could result in poor speech communication, lack of adequate hearing protection, or both. If the individual has a hearing loss impairment, then the choice can be even more difficult in order to obtain an optimal HPD-noise combination, especially if speech communication is critical.

For normal hearing individuals, the effects of an HPD on speech intelligibility will be largely influenced by the interactive effects of the noise spectral characteristics and the HPD attenuation characteristics. For instance, if a certain HPD has strong attenuation characteristics at 2000 Hz and the ambient noise also contains its strongest energy at that frequency, then largely due to reduction in cochlear distortion, speech discrimination should not be adversely affected (and perhaps may be facilitated) by the HPD. If, on the other hand, the HPD attenuation characteristics are weak at 2000 Hz, then the individual wearing the HPD may experience masking of speech sounds by the noise, which "gets through" the HPD at this critical frequency. Consequently, for the normal hearing individual, the relative advantage of one type of HPD over another is to some extent dependent on the type (spectral characteristics) of the noise environment and the spectral attenuation characteristics of the HPD. For those individuals with a hearing impairment, the additional factor concerning the specific frequencies at which hearing deficiency occurs must be considered when selecting an HPD for a specific noise environment where verbal communication must be maintained.

While HPDs do not typically hinder those individuals with normal hearing in noise levels above 80 dB, they can cause speech discrimination problems for people with certain types of hearing loss. This is especially true for people with high frequency hearing loss since HPD attenuation tends to be most effective in the higher frequency ranges. Compounding this problem is presbycusis, which predominantly affects the higher frequencies and progresses with age (Hawkins and Johnsson, 1976). However, as discussed by Berger (1982b), while HPDs may hinder speech intelligibility for those with hearing loss, the alternative of not wearing them will only increase the intelligibility problem. That is, additional noise exposure will further degrade hearing, which in turn will deteriorate speech intelligibility.

For both normal hearers and those with hearing loss, the use of HPDs in noise levels below about 75-80 dB may significantly reduce speech intelligibility. Individuals with above moderate degrees of either high frequency or flat hearing loss are at a greater disadvantage than normal hearers in these low-noise environments. Therefore, it is typically not recommended that HPDs be used in noise levels below 75-80 dB (regardless of degree of hearing loss) if verbal communication is essential, unless the presence of high intensities at particularly dangerous frequencies warrants their use for protection purposes. Since such protection is often needed, other provisions for communication rather than the elimination of HPDs, should be made.

As previously mentioned, increasing the S/N ratio does improve intelligibility performance. However, the gains in speech intelligibility for those with hearing impairments at a high S/N ratio (versus a low S/N ratio) are rarely equivalent to gains experienced by normal hearers. Moreover, increasing the S/N ratio in a given situation may simply not be a feasible alternative for the HPD user.

Finally, additional factors such as voice level and quality, visual cueing, language fluency, and HPD insertion strategies (affecting achieved attenuation) contribute to the influence of an HPD on speech intelligibility. However, maintaining optimal voice level (e.g., by shouting) and voice quality is sometimes not possible. Furthermore, visual cueing requires face-to-face visual contact which may not be feasible, and HPD insertion strategies may require additional effort in training programs with the added assumption that workers are adequately motivated to learn.

The overall conclusion suggested by prior research is that the use of HPDs in high noise environments will probably not degrade, and in some cases will enhance speech communication for individuals with normal hearing. However, as a representative population of industrial workers includes many with hearing loss impairments, these individuals may experience speech communication problems when wearing HPDs in noise.

The selection of an HPD cannot be made in an arbitrary fashion. One solution (which has been offered in the context of providing enhanced detection of warning signals) is to carefully select an HPD which would minimize the necessary amount of attenuation in the speech range and thus enhance the amount of speech intelligibility provided. However, a preferable solution would be to institute a hearing conservation program that takes into account both individual differences in hearing impairment and specific industrial noise environments when selecting an HPD. In such a program, the emphasis would be on "custom" fitting the individual with a certain HPD, depending on the two above-mentioned factors and others as well. In this way, the optimal protection for a given noise environment would be insured while still providing for adequate speech communication.

The present study. Previous research has concentrated on the investigation of one to three variables affecting speech communication in noisy industrial environments. The present study, discussed in the ensuing pages, addressed four independent variables and one blocking variable in factorial (interactive) fashion. These variables included: listener's hearing configuration (either unoccluded or occluded with a specific HPD-type), speaker's voice level determining S/N ratio (as empirically-verified under either occluded or unoccluded speaker conditions), ambient noise level (60 or 83 dBA), and ambient noise spectrum (low frequency, white approximation, or high frequency). Listener's hearing level (normal hearing, slight loss, and moderate loss) served as a blocking variable. Each of these factors has potential for enhancing or degrading speech communication, either singly or interactively. However, the collective group has not been investigated in an interactive fashion.

The basics of the present study were as follows. A selected set of HPDs was worn by three groups of subjects with different hearing levels while in the presence of various ambient noise intensity levels and spectral types. Speech material (isophonemic words) was presented via loudspeakers to the subjects at two S/N ratios for each noise level used. These S/N ratios represented realistic variations in the speaker's (talker) voice level when he was occluded or not occluded. The aim of this research was to evaluate the effects of different HPD types (earplug, earcap, and earmuff) on subjects' speech discrimination in typical industrial noise backgrounds. The HPDs and industrial noises used were selected from among those investigated in the Casali et al., (1985) study.

RESEARCH OBJECTIVES

With regard to the evaluation of effects on speech reception and discrimination, the experimental objectives of this research study included:

1. The evaluation of different HPD types which are representative of those currently marketed and commonly used in industrial environments.

2. The evaluation of noise intensity levels which are representative of those found in industrial settings but which do not endanger unoccluded subjects.

3. The evaluation of three ambient noise spectral types characterized by low, white (approximation), and high frequency profiles. The low and high frequency noises were representative of typical industrial machinery-emitted noises.

4. The evaluation of speech S/N ratios which are representative of actual speech levels attained in quiet or noisy conditions and while the speaker is occluded or not. (This accounts for the "occlusion reflex.")

5. The evaluation of subjects with different hearing levels through the use of hearing level blocks.

The practical objectives of this research study included:

1. The controlled analysis of speech reception and discrimination under a variety of conditions somewhat typical of manufacturing industries.

2. The provision of HPD-related speech communication information which will benefit HPD wearers in providing the practical advantages of one type of HPD over another for both hearing protection and speech reception/discrimination in a given noise condition.

3. The contribution of valuable HPD-related communication information which will benefit industrial conservation programs.

EXPERIMENTAL METHODOLOGY

Experimental Design

A mixed-factors, partial hierarchical design was used for data collection and analysis (Figure 1). Subject's hearing configuration was a within-subject variable with 4 levels (3 HPDs and an unoccluded condition). Ambient noise level was a within-subject variable with two levels (60 dBA and 83 dBA). Ambient noise spectral type was a between-subject variable with 3 levels (low, white (approximation), and high frequency spectral characteristics). Speaker voice level was a within-subject variable with four levels (63 and 65 dBA in a 60 dBA noise level, and 82 and 88 dBA in a 83 dBA noise level). The speaker's voice level was determined by his hearing configuration (earmuff-occluded or unoccluded) and nested within the ambient noise level. Subject's hearing level was a blocking (between subjects) variable with three levels (normal hearing, slight loss, moderate loss). Next, each independent variable is discussed in detail.

Subject hearing level (blocking variable). Subjects were tested for hearing ability and assigned to an ambient noise type (the between-subjects variable) based on their scores, so that an equivalent cross-section of hearing levels existed in each condition. That is, after all subjects were audiometrically tested, their hearing levels were ranked in a continuum, the continuum was divided into thirds, and an equal number of subjects were randomly selected from each third and assigned to each ambient noise type. In this manner, subject hearing

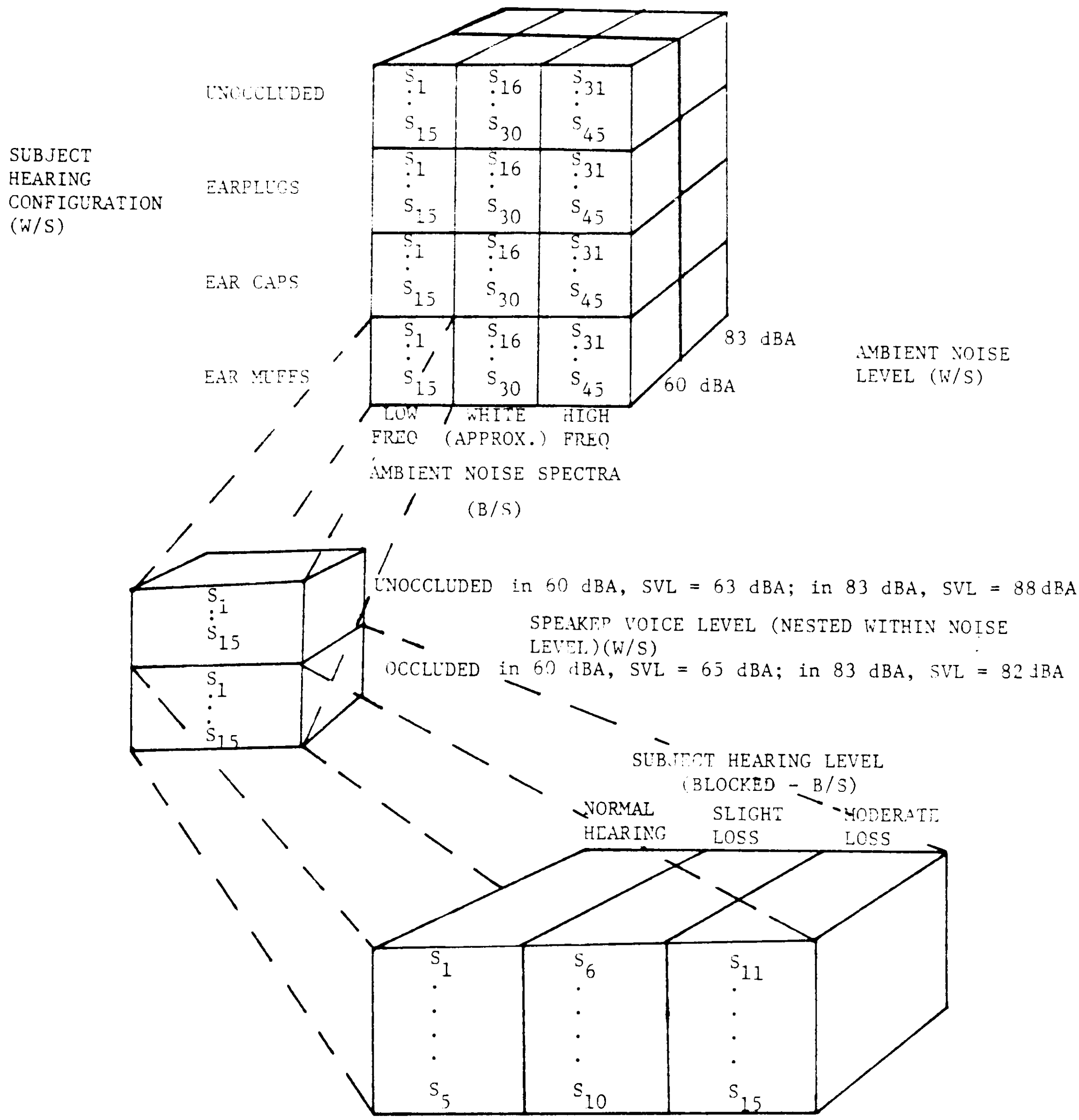

Figure 1. Experimental design matrix with independent variables and subject assignment.

level served as a blocking variable. Subject gender did not constitute a strict blocking variable because of the odd number (45) of total subjects required, 15 per ambient noise type. Of 23 males and 22 females, the gender distribution over the three noise types was eight males and seven females, or vice versa, for each noise type.

Subject hearing configuration (HPDs). Three HPDs, an earplug, an earcap, and an earmuff, were selected from among those of some 50 vendors reviewed for the Casali et al., (1985) study and utilized in this present study, along with an unoccluded condition. These constituted the levels of the subject hearing configuration (SHC) variable. The HPDs (and the manufacturer's reported NRR) included: E-A-R malleable foam earplug (NRR = 29 dB), Flents Model 055 Peace and Quiet Headband earcap (NRR = 17 dB), and Willson Model 365A Sound Barrier earmuff (NRR = 26 dB). The HPDs are shown in Figure 2. As discussed previously, HPDs vary in their attenuation of a given sound signal, whether the signal consists of speech and/or noise, due to variations in construction materials, design, fit, and other factors. Therefore, in order to evaluate the effects of different HPD types, a representative HPD from each of the three common HPD categories (earplugs, earcaps, and earmuffs) was selected for use and evaluation in this study. It should be noted that the selected HPDs differed considerably in their NRR ratings as well as in their spectral attenuation characteristics.

During each experimental session, subjects donned one type of HPD (earplug, earcap, or earmuff) or remained in an unoccluded condition.

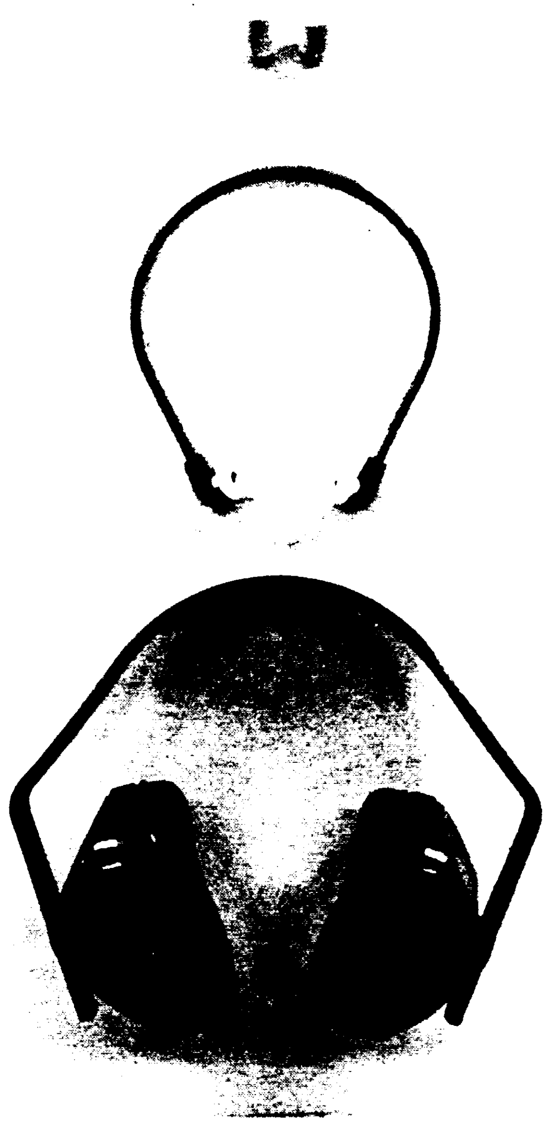

Figure 2. HPDs used in the study including: from top, user-molding E-A-R foam earplugs, Flents Model 055 Peace and Quiet Headband (earcaps) and Willson Model 365A Sound Barrier earmuff.

Again, as discussed earlier, an HPD will attenuate both signal and noise of similar spectral patterns to the same degree, and thus, may reduce speech reception and discrimination for the listener. Therefore, unoccluded as well as the occluded conditions (for each subject) were necessary to evaluate any differential effects between speech reception and discrimination with and without HPDs.

In order to ensure fit and wearing uniformity across all subjects, each subject received a set of comprehensive insertion/donning instructions (termed "detailed instructions") developed and tested by Casali et al., (1985). The detailed level of instruction consisted of a longer and more detailed version of the manufacturer's instructions, including supportive pictorial presentations. The complete instructions are shown in Appendix A. In addition, subjects were also verbally instructed before fitting the HPD and visually examined after the fitting by the experimenter.

Ambient noise intensity level. Two noise intensity levels, 60 dBA and 83 dBA, were used with each of the three types of ambient noise spectra. These levels were representative of low and moderately high industrial noise levels, respectively. At the high end, 83 dBA was selected so that the subjects would not be exposed to noise intensities exceeding the new OSHA standard (85 dBA per 8-hour day time weighted average). Even so, their exposures were only a fraction of the work day duration.

Ambient noise spectral characteristics. Two industrially-derived background noises, one characterized by a bias in low frequency sound pressure and another having high frequency bias were used along with an electronically-synthesized white noise approximation. Again, the two industrial noise types were selected from among those obtained in the Casali et al., (1985) survey. In that study, measurements of several noises were conducted at local manufacturing plants, including 1/3 octave spectral analysis in situ and subsequent recording. The noises were emitted from the following machines: vibro-energy finishing mill, numerical-control (NC) drilling machine, manual notcher, contour saw, band saw, engine lathe, foundry furnace, 27-ton press, sand blaster and dust collector, pedestal grinder and surface grinder. Each of the noise measurements was conducted using the ANSI S1.13-1971 field method for measuring sound pressure level, while the spectral analyses were performed in accordance with recommendations from the USAS S1.6-1967 standard. A Larson-Davis (ANSI Type 1-ANSI S1.4-1971) Model 800-B acoustic analyzer was used for all field and laboratory noise spectral analyses.

The two industrial noises chosen for the study were those emitted from the foundry furnace and the contour saw. The foundry furnace noise was characterized by a positively skewed spectrum with strong energy components in the lower frequency range and sharply decreasing sound pressure level with increased frequency. The primary concentration of energy was located in the range of 75-500 Hz. The spectrum for this noise type, termed "low frequency" noise, is shown in Figure 3. Conversely, the contour saw spectrum was negatively-skewed with weak energy components in the low frequency ranges and a

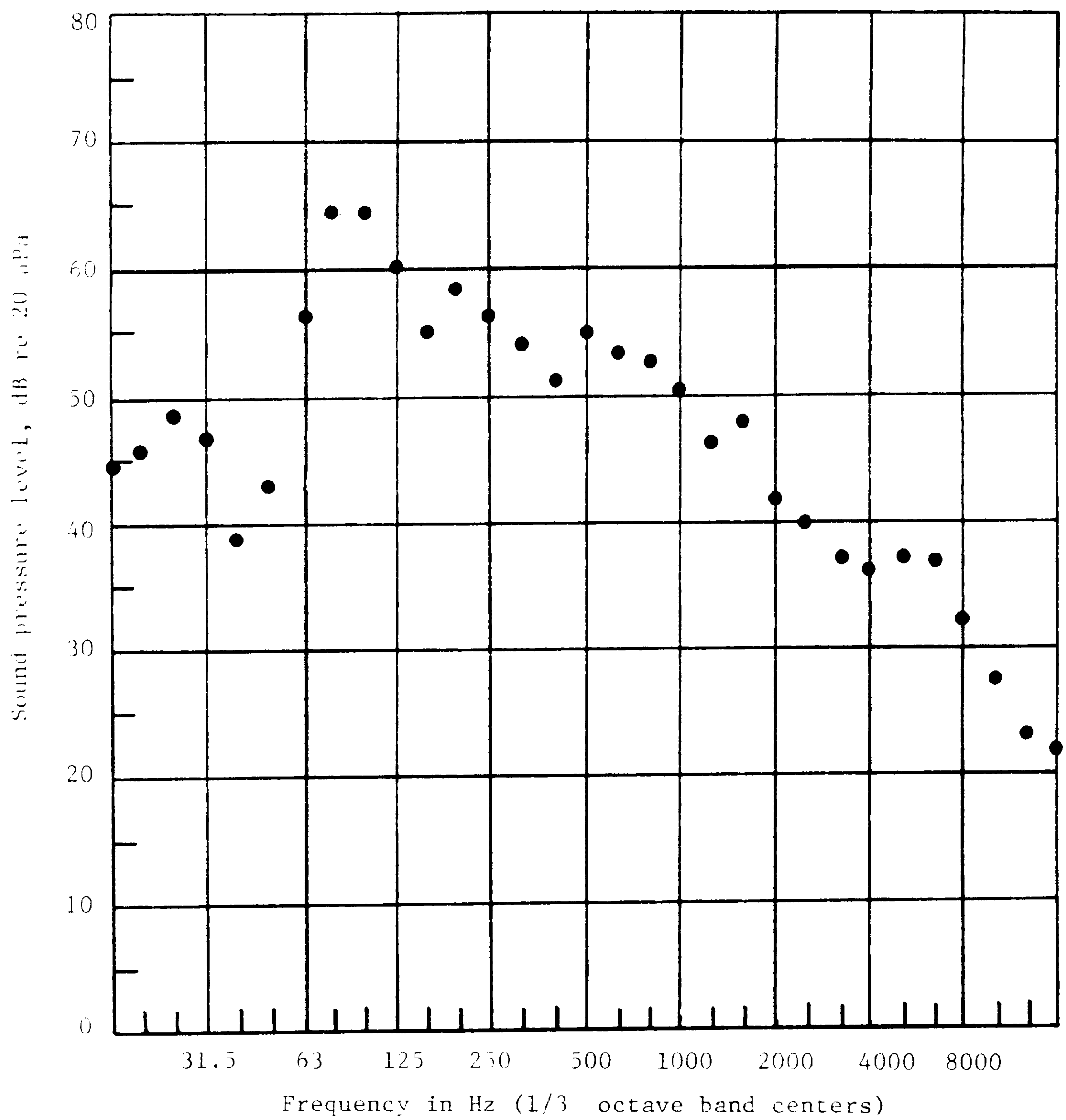

Figure 3. 1/3 OB noise spectrum for low frequency (foundry furnace) spectral noise type. Readings are 10-second integrated measurements, linear sound pressure level. Note: Loudspeaker output was negligible below 50 Hz; in situ spectrum shown.

continuous rise in energy as frequency increased. The primary concentration of energy in the high frequency noise type was in the range of 1000 - 8000 Hz (see Figure 4--in situ noise spectrum shown). Note that loudspeaker response was negligible below 50 Hz.

The third noise spectral type was an approximation of white noise. White noise was generated via an audiometer masking network and presented from magnetic tape through an amplifier-equalizer-loudspeaker system to produce the broadband noise spectrum shown in Figure 5. This noise was representative of typical building background noise such as that resulting from forced-air heating and ventilation systems.

Once playback of a noise condition began, the noise was temporally constant throughout the experimental session. There was no intermittent or significant variation within any noise type over time.

Speaker's voice level nested within ambient noise level. Prior to the initiation of the speech discrimination study, a single individual, serving as the presentation source for all speech signals, was recorded while reading the predetermined speech material. The speech signal (word list) presentations were prerecorded and played back, rather than presented live, so that any variation in the speaker's voice level or voice quality due to fatigue or other effects would be minimized. Furthermore, the playback level could be held constant. The recorded presentations were presented to the listeners (subjects) at a specific level for the occluded and unoccluded speaker conditions, for each ambient noise level used (60 and 83 dBA). That is, the gain on playback of the recorded speech signals was adjusted to one of four

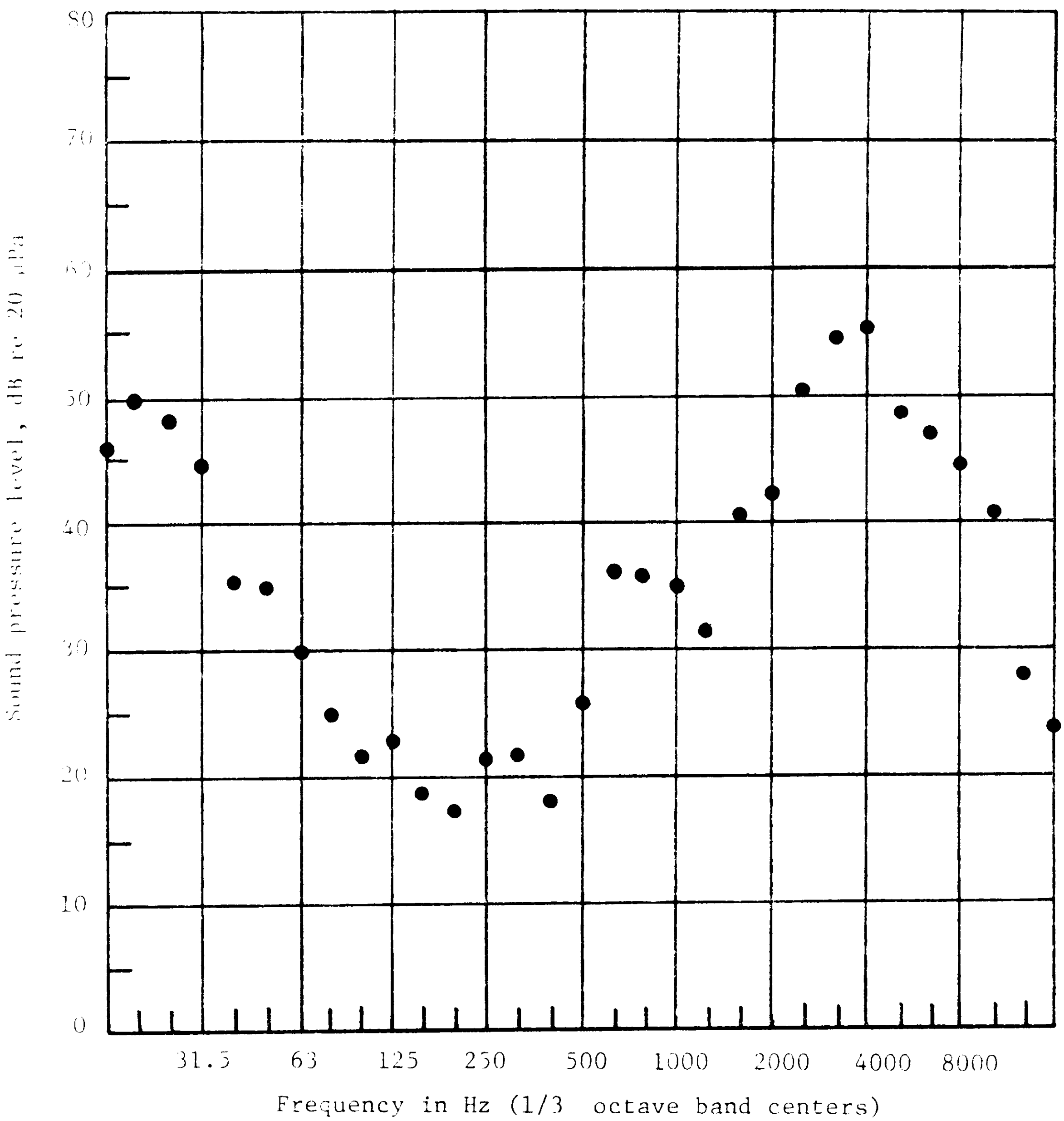

Figure 4. 1/3 OB noise spectrum for high frequency (contour saw) spectral noise type. Readings are 10-second integrated measurements, linear sound pressure level. Note: Loudspeaker output was negligible below 50 Hz; in situ spectrum shown.

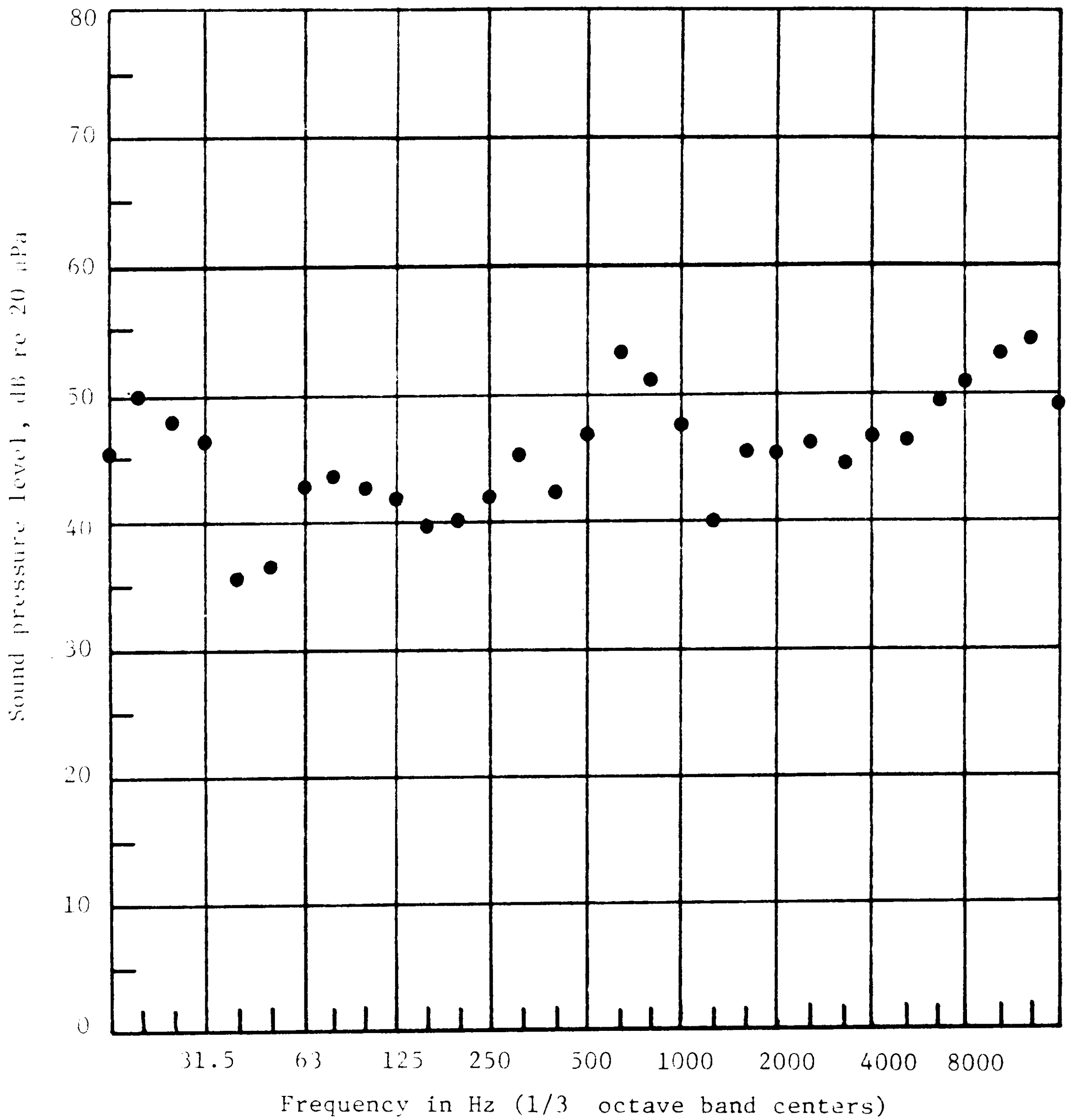

Figure 5. 1/3 OB noise spectrum for white noise approximation. Readings are 10-second integrated measurements, linear sound pressure level. Note: Loudspeaker output was negligible below 50 Hz.

levels depending upon the combination of experimental conditions under which a particular word list was spoken (unoccluded/occluded and 60/83 dBA ambient noise level). The words were delivered at a rate of approximately 1 word every 5 seconds.

As mentioned in the literature review, a person's voice level drops due to the Lombard effect in an occluded condition compared with an unoccluded condition. Since this resulting decrease in S/N ratio may affect speech discrimination for the listener, the influence of occlusion and ambient acoustic conditions on the speaker's voice level was deemed important and was therefore determined in a pilot study (see Appendix B).

During the word list recordings, each of the speech signals was uttered with equal power, rather than in natural fashion, to maintain consistency across words. The male speaker (who made all the recordings) monitored his own utterances and voice intensity level via a VU meter throughout the duration of the word list recording session. This visual feedback was used to help the speaker maintain consistency in voice power throughout the word list presentations. The speech spectrum for the male speaker's voice is shown in Figure 6. This spectrum was obtained with the 1/3 octave band analyzer on its peak setting. The plotted values represent the mean of three presentations of a 10-word list. During the actual study, the recorded speech material was presented to the subjects (two at one time) through two loudspeakers per subject.

To determine speech levels, nested within ambient noise conditions, which would be representative of a speaker under occluded

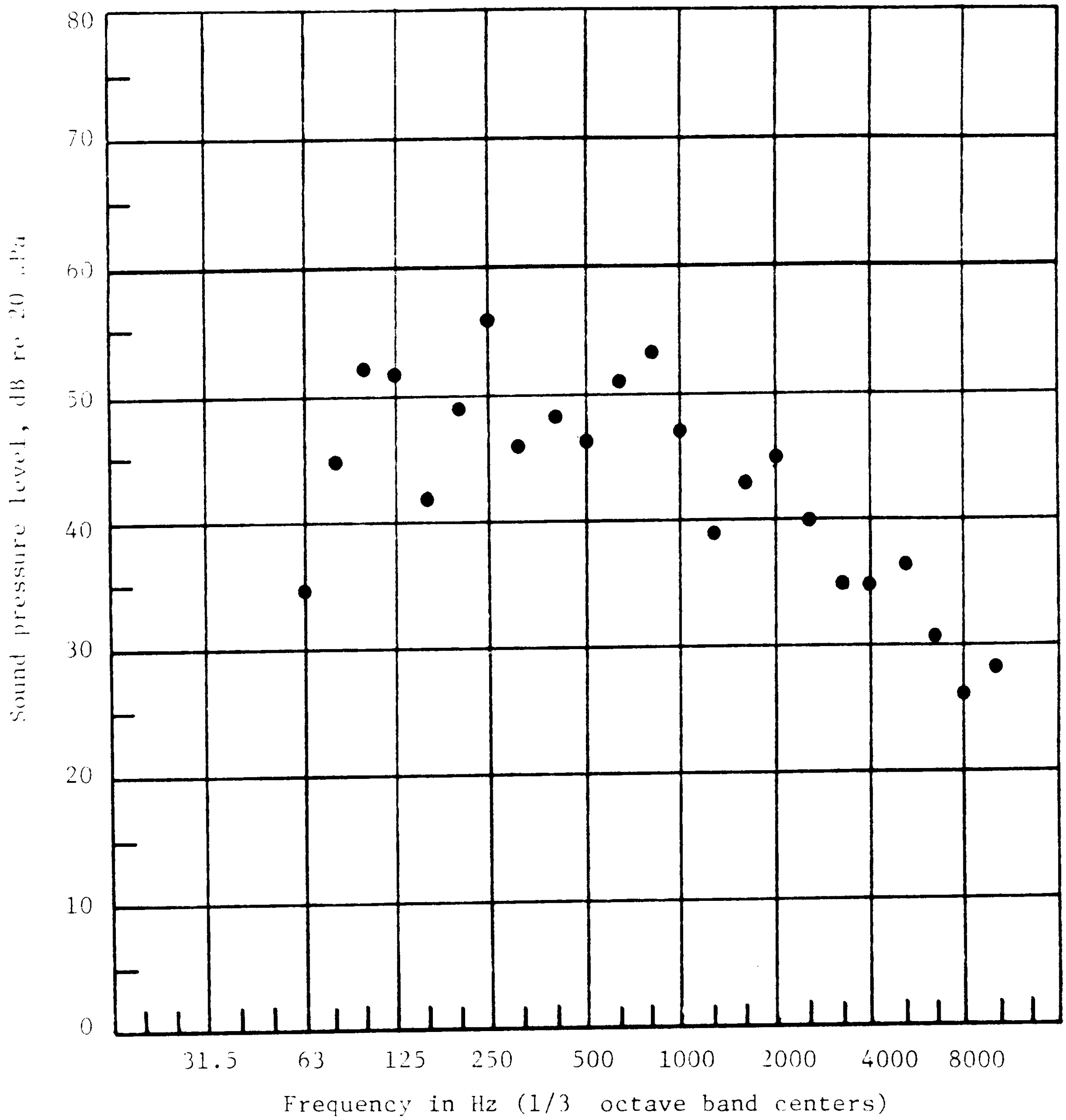

Figure 6. 1/3 OB noise spectrum for the speaker's voice level (mean of three readings) during the presentation of a 10-word list. Readings taken at peak meter setting, linear sound pressure level.

and unoccluded conditions, the pilot study described in Appendix B was performed. For both 60 and 83 dBA ambient noise levels, it was desirable to hold S/N ratio in the speaker unoccluded paradigm to +5. Using the pilot study results for both 60 and 83 dBA, the achieved voice level was reduced by 2 dBA for occluded speakers in 60 dBA noise and by 6 dBA for occluded speakers in 83 dBA noise. This resulted in final speaker voice level values in dBA, nested within ambient noise level, of the following:

		Speaker Configuration	
		Occluded	Unoccluded
Ambient	60 dBA	63	65
Noise Level	83 dBA	82	88

It should be noted that with this design, the speaker voice level values were a hierarchical variable, nested within the two levels of ambient noise in the data analysis procedures described later.

Individual differences and order effects. As previously mentioned, individual differences in hearing level for the between-subjects variable of ambient noise type were controlled in the design through blocking. It should also be noted that the within-subject variables of ambient noise level and subject hearing configuration were presented according to a balanced Latin-square ordering to guard against practice effects. It was not possible, due to the necessity of requiring such a large number of subjects, to latin-square the presentation order of speaker voice level (four levels) as well. Therefore, its order was randomized across subjects. Given that the four levels of voice level were combined with eight combinations of noise level and subject hearing configuration, it is unlikely that subjects could have detected the exact voice level present. Furthermore, the randomization hopefully precluded any order effect bias with the speaker voice level variable.

Speech test material: isophonemic words. The dependent variable under investigation was speech discrimination, which can be operationally defined as a measure of a person's ability to distinguish between different speech sounds or words (Rintelmann, 1979). As discussed in the literature review, speech discrimination is different from speech intelligibility in that the latter measure focuses on word, phrase or contextual meaning (Kryter, 1985), while the former specifically addresses the ability to distinguish among speech sounds.

The test material used to assess speech discrimination consisted of monosyllabic, isophonemic words described by Boothroyd (1968). These words are of the consonant-vowel-consonant (CVC) type and are arranged in 15 lists of 10 words per list. (The actual lists used in this study appear in Appendix F.) Each word list was created using different arrangements of the same set of 30 English phonemes.

For the purposes of the present study, word lists longer than Boothroyd's 10 words per list were needed. Therefore, 17 word lists were created from the original set (one for each experimental condition and a practice list) with each new word list containing 30 words. Each of the 17 word lists were created by combining three of the original word lists in a manner which minimized the repeated use of each original word list. The matrix for the word list combinations is shown in Appendix G. The assignment of combined word lists to experimental conditions was counterbalanced across subjects to protect against potential ordering effects with specific list sequences.

Monosyllabic words were chosen as the test material for this study rather than multi-syllable words, multiple words, or sentences for the primary reason that the use of single-syllable words prevents any interaction between syllables which could otherwise occur (Lindeman, 1976). Thus, with the use of monosyllabic words, one can assess listener auditory performance in terms of reception and discrimination of words (or in this case, phonemes) alone without depending on measures of an individual's associative abilities, level of intelligence, or the extent of his or her vocabulary.

Dependent measure: phonemes. A further distinction must be made between "phonemes" and "words" because the specific measure of speech reception and discrimination for this study was the percentage of correctly written phonemes derived from the monosyllabic words. Phonemes are the basic units of speech which distinguish one word from another (e.g., the b of bat and the m of mat are two English phonemes). The advantage of using phonemes rather than word scoring, according to Boothroyd (1968), is that phonemic scoring provides a more valid estimate of a subject's ability to distinguish between different speech sounds by reducing language skill advantages as well as interlist differences. Consequently, given that the main interest of this study was to assess speech reception and discrimination (rather than meaning or context), the use of basic speech sounds (phonemes) was an appropriate measure.

Phonemic scoring (compared with word scoring) increases the degrees of freedom obtained from a list of CVC monosyllabic words by a factor of three (three phonemes/word); thereby increasing the number of measurable test items, while reducing the amount of test score variability. Moreover, the use of Boothroyd's validated, shorter lists (combined to yield 30 words per list), as opposed to traditional 50-word lists, reduces testing time and minimizes subject fatigue, practice effects, and noise adaptation effects.

Subjects

Paid volunteers from the Virginia Tech university community served as subjects. The total of 45 subjects consisted of 23 males (mean age 21.9 years, standard deviation 3.3 years) and 22 females (24.6, 7.9). Potential subjects were screened for qualifications via a pre-experimental questionnaire (Appendix D).

The requirements for participation included: (1) subject's native speaking and writing language was English; (2) subject had no extended experience involving speech communication while wearing an HPD; (3) subject had not previously been involved in experiments concerned with HPD usage, audiometric threshold measurements, or speech reception/discrimination testing; (4) subject had no current or prior history of problems related to otopathic disorders (e.g., tinnitus, excessive ear-wax); and, (5) subject underwent an audiometric test and met the hearing level criteria as defined in the forthcoming procedures section. The experimental procedures were then fully explained to each eligible subject. Finally, the subjects were asked to read and sign an informed consent document (Appendix E) indicating their desire to participate in the experiment.

Experimental Apparatus

Facility. The experimental facility for both the pilot and main studies consisted of an anechoic chamber with 120 Hz low frequency cutoff and 6 Hz vibration isolation located in the Auditory Systems Laboratory at Virginia Tech. The ambient octave-band sound levels in the chamber (when no signal is present) are: 21 dB at 125 Hz, 19 at 250 Hz, 17 at 500 Hz, 18 at 800 Hz, 16 at 1000 Hz, 16 at 2000 Hz, 16 at 3150 Hz, 15 at 4000 Hz, 15 at 6300 Hz, 15 at 8000 Hz. Via open-cell foam wedge treatment on the walls, floor, and ceiling, the chamber provides an approximate free-field environment for sounds of greater than 120 Hz.

For the experiment, the chamber housed four loudspeakers which were used for presentation of the signal words and ambient noises, two chairs for subjects, a remote microphone for speech and noise level calibration, and a two-way intercom to monitor the word presentations and allow for subject-experimenter communication. The overall chamber configuration is shown in Figure 7.

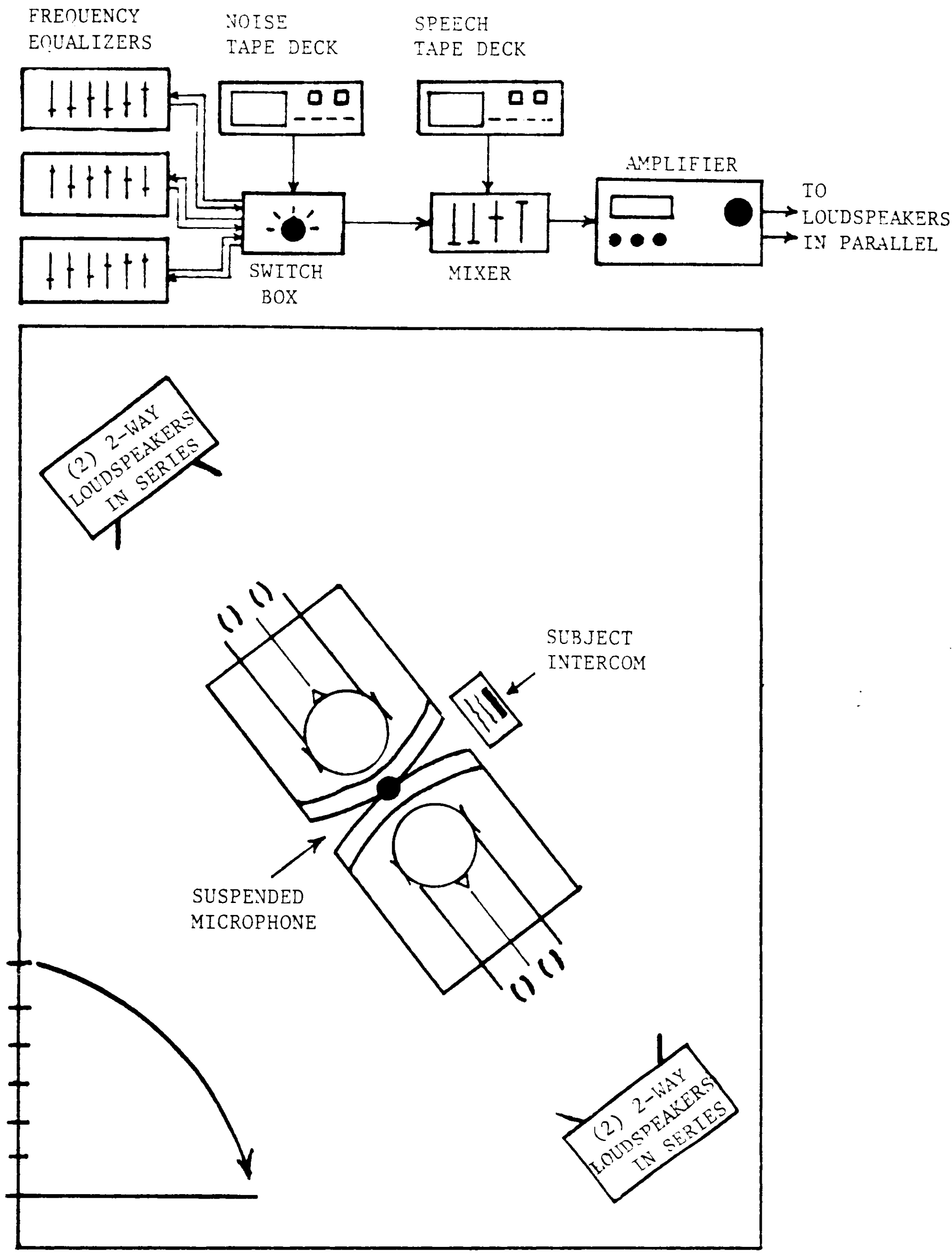

Figure 7. Schematic of experimental test facility.

The experimental arrangement consisted of two subjects in the center of the chamber, seated back-to-back as shown in Figure 8. A pair of identical loudspeakers, wired in series and stacked vertically on their sides, were suspended in front of each subject and positioned in two of the chamber corners so that the front face of each loudspeaker pair was parallel to the plane of each subject's face. Both pairs of loudspeakers were positioned equidistant from their respective subject's ears and ear height level. This arrangement allowed for running of two subjects at a time with no interference from one subject to the other.

A 1/2-in pressure-response microphone (Bruel and Kjaer Model 7013) used for speech and noise level calibration was suspended directly overhead and centered between the subject pair.

Sound generation/presentation system. The experimental speech signal and background noise conditions were produced using a system consisting of a Scott Model 458A integrated stereo amplifier, Realistic Model 32-1100A stereo mixer, Ross Model R31M and Realistic Model 31-2000A frequency equalizers, a custom made three-position equalizer junction box, Teac Model 124 cassette tape deck, Realistic Model 14-633 cassette tape deck, and four Infinity (Model RS-9B) two-way loudspeakers. Two Realistic Model 43-207A two-way intercoms and an Electro-Voice Model 6216 microphone were used for subject-experimenter communication. These components were integrated as shown in Figure 7, while the overall experimental layout appears in Figure 9.

Figure 8. Arrangement of subjects and loudspeakers in anechoic chamber. (Only one pair of Loudspeakers shown.)

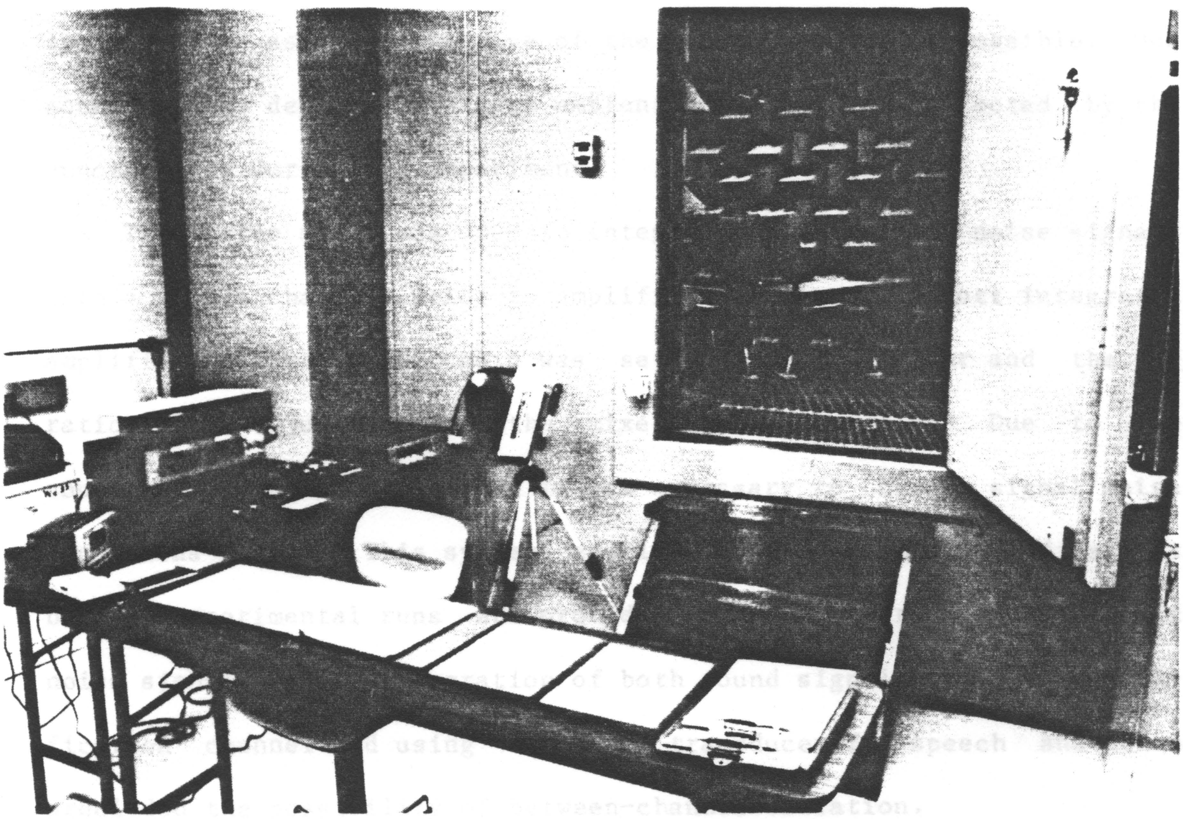

Figure 9. Experimenter's station with sound presentation equipment and anechoic chamber.

The Teac deck was used for playback of the ambient noise recordings on TDK-AD90 tapes. The Realistic deck was used for playback of the isophonemic word lists which had previously been recorded in male voice on Triad MG-X90 metal tape. Output of the Teac (noise) deck was equalized so that the noise spectra, as reproduced through the loudspeakers, was as representative of the original noise as possible. One equalizer was dedicated to each ambient noise type and selected by the junction box during the experiment.

The stereo mixer was used to integrate word list and noise signals onto a single channel prior to amplification via the Scott integrated amplifier. The overall gain was set on the amplifier and the S/N ratios were adjusted using the mixer slide controls. Due to the counterbalancing of conditions it was necessary to change signal/noise conditions often. This system enabled simple calibration adjustment between experimental runs and provided precise control of speech and noise signals. The integration of both sound signals onto one amplification channel and using a common transducer for speech and noise precluded the possibility of between-channel variation.

Amplifier output was fed in parallel to each pair of loudspeakers which were wired in series. The four Infinity RS-9B loudspeakers were arranged in the anechoic chamber (Figure 8) so that the drivers were at 90 deg to the subjects' faces. The participants were informed of the location of both the signal and the noise sources and told to orient themselves in that direction at all times so that variance due to positional cues would be minimized. Each of the two-way loudspeakers contained a 16.51 cm (6.5 in) polypropylene woofer and a 2.54 cm (1 in) polycell tweeter, with a crossover frequency of 4500 Hz (Infinity).

Calibration equipment. The Larson-Davis Model 800-B acoustic analyzer was used for calibration of all signal presentation levels and for audiometer verification prior to the hearing tests. The device is a sound-pressure-level (SPL) meter with 1/3 octave and octave selectable filters. The device meets ANSI S1.4-1971 (Type 1) for precision sound-measurement equipment. The analyzer, in conjunction with the Bruel and Kjaer Model 7013 1/2-in random incidence, pressure response microphone and Model 2619 preamplifier, was used for calibration of the word lists and ambient noise levels in the anechoic chamber prior to each experimental run. Furthermore, the overall signal levels were monitored throughout a run using this instrument.

The audiometer calibration was achieved using a Bruel and Kjaer Model 7023 1-in microphone and Larson-Davis Model AE-100 artificial ear.

Audiometric testing facility. The test chamber used for testing subjects' hearing during the screening session was an Industrial Acoustics soundproof room. The room is vibration-isolated and has its own ventilation system.

A Beltone Model 114 clinical audiometer was used for presenting pure-tone stimuli for the hearing tests. Right and left ear hearing was tested using noise-isolating earphones.

Experimental Procedures

The experiment was divided into two sessions. In the first session, subjects were screened as to qualifications and were audiometrically tested for hearing level. The second session (at a later date) was used to collect data for each of the treatment conditions in the speech discrimination experiment.

Session one: subject screening. In order to verify that the subject was eligible for participation, he/she was asked to complete a pre-experimental questionnaire (Appendix D). Eligible subjects were then asked to read an informed consent document (Appendix E). During this time, any questions initiated by the subject were answered by the experimenter, as long as the answer did not pre-bias the experiment. The subject then signed the informed consent document, provided he/she agreed to participate.

Eligible subjects were then tested for hearing level in accordance with the ANSI S3.21-1978 (Methods for Manual Pure-Tone Audiometry) standard. Each subject was tested for left and right ear hearing thresholds at pure-tone frequencies of 125, 250, 500, 1000, 2000, 4000, and 8000 Hz. Three consecutive ascending thresholds were determined for each test frequency using a five pulse duration on each threshold test. The average of the three thresholds determined the mean estimate of hearing threshold for that frequency. Each trial was comprised of five complete on-off tone cycle presentations. Time between pulses as well as between trials was varied to minimize "anticipation" effects with the minimum duration exceeding 3 seconds. The threshold of audibility was assumed to occur when a subject responded on or before the fourth pulse.

A grand-mean hearing threshold score for each subject was derived. First, the mean threshold level for left and right ears was computed for each test frequency from the three trials. The mean of all the averaged threshold levels across frequency was then determined for each ear. Finally, the grand-mean scores were derived by computing the average of the left and right ear means.

Next, the three categories for blocking hearing level were formed by subdividing the continuum for all subject grand-mean scores into three groups containing equal numbers of subjects. The assignment of a subject to a particular group was based on the location of their grand-mean threshold level score within the continum of grand-mean scores for all subjects. Subjects from each group were then assigned to each ambient noise type, as previously discussed.

For the purposes of blocking, a subject was considered to have normal hearing if his/her grand-mean hearing threshold score was between -1.9 dBHL (hearing level) and 3.5 dBHL. For the slight loss hearing level, the criterion was a grand-mean score between 3.9 dBHL and 6.7 dBHL. The criterion for a moderate loss hearing level was a grand-mean score between 6.9 dBHL and 23.4 dBHL.* Any subjects with

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* The terms "normal," "slight," and "moderate," loss are not meant to imply a diagnosis on the level of hearing acuity. They are simply ordinal descriptors used to denote the differences in hearing acuity for the three groups comprising the continuum of subjects tested for this study.

bilateral mean (across frequency) differences greater than 6 dBHL were not used in the experiment.

Session two: speech discrimination data collection. The second session lasted approximately two hours during which speech discrimination data were collected. For each experimental session, two subjects seated in the anechoic chamber listened to the recorded monosyllabic words presented through the loudspeakers (Figure 8). During the presentation of each word list, the subjects recorded the words he or she heard on a response sheet (Appendix H), as each word was presented. Written replies were used rather than spoken replies so that any misunderstandings (a probable source of error) which could have occurred with the use of tape recordings of subject responses in noise were removed from the study.

Specifically, the following sequence of procedures was followed for each experimental session:

1. Two subjects, randomly selected as to their hearing level, were asked to read the experimental instructions (Appendix I) and were seated in the chamber.
2. Subjects were practiced in the discrimination task (see below).
3. A level of noise spectral type (between-subjects variable) was selected as determined by the experimental design.
4. Both subjects were given the appropriate HPD condition, a level of ambient noise intensity, and a speaker voice level (word list presentation level) in accordance with the latin-

square design.

5. Prior to beginning the discrimination tests, the subjects donned the HPD according to the detailed instructions (Appendix A) or remained unoccluded, depending on the condition. HPD fit was verified and adjusted by the experimenter if needed.

6. A list of recorded monosyllabic words was presented to the subjects at a rate of approximately 1 word every 5 seconds (requiring approximately three minutes per list).

7. Steps 4 through 6 were repeated until the pair of subjects had experienced all within-subject treatment combinations.

8. At the completion of the session, the subjects were debriefed, paid, and allowed to leave.

The process was repeated for another pair of subjects until all subjects were tested.

The practice session consisted of three initial word list presentations of ten words per list under three sample conditions (all using the "white" noise approximation) including: subjects unoccluded, 60 dBA ambient noise level, speaker's voice level at 65 dBA (unoccluded); subjects unoccluded, 83 dBA ambient noise level, speaker's voice level at 88 dBA (unoccluded); and subjects earmuff-occluded, 83 dBA ambient noise level, speaker's voice level at 82 dBA (occluded) respectively. The practice tests were conducted (with feedback) to ensure that the subjects understood their task, to acquaint the subject with a subset of the diverse range of treatment conditions, and to overcome any initial learning.

RESULTS

The data analysis consisted of four parts. Initially, an analysis of variance (ANOVA) was applied to the data for the five-way mixed-factors, partial hierarchical design. The treatment means for significant main effects (only those with more than two levels) were then analyzed using student Newman-Keuls multiple range tests to determine the specific loci of mean differences. First, for the significant interactions, graphs of data mean values were constructed to illustrate and evaluate treatment mean score interactions. Next, comparisons which were of interest among specific treatment means were tested for significance using the Newman Keuls multiple-range test.

The ANOVA analysis was conducted on an IBM 3090 computer using the statistical analysis system (SAS, 1985). The Newman-Keuls multiple-range tests were conducted in accordance with the procedures illustrated in Weiner (1971).

Overall Five-Way ANOVA on Word List Discrimination Scores

The mixed-factors ANOVA performed on the word list response scores resulted in the summary table appearing in Table 1. All independent variables were tested as fixed-effects variables for the purpose of generating expected mean squares and for identifying *F*-ratios in this ANOVA. Subjects were considered as a random-effects variable. In Table 1, the key for the abbreviations used for each source of variance are given. The dependent measure consisted of the percentage of

Table 1

ANOVA Summary Table for the Speech Reception/Discrimination Analysis

Source	dF	SS	*F*
Between-Subjects			
Hearing Level (HL)	2	938.56	1.97
Noise Type (NT)	2	15580.44	32.65***
HL x NT	4	339.83	0.36
S/HL,NT	36	8588.79	
Within-Subjects			
Subject's Hearing Configuration (SHC)	3	897.09	4.45**
SHC x HL	6	1104.39	2.74*
SHC x NT	6	689.11	1.71
SHC x HL x NT	12	764.18	0.95
SHC x S/HL,NT	108	7262.95	
Noise Level (NL)	1	3329.49	51.36***
NL x HL	2	444.30	3.43*
NL x NT	2	2443.81	18.85***
NL x HL x NT	4	35.69	0.14
NL x S/HL,NT	36	2333.76	

(Continued on next page)

Table 1 (Continued)

ANOVA Summary Table for the Speech Reception/Discrimination Analysis

Source	dF	SS	F
Speaker's Voice Level (SVL/NL)	2	16548.85	344.70***
SVL/NL x HL	4	101.68	1.06
SVL/NL x NT	4	2496.93	26.00***
SVL/NL x HL x NT	8	70.23	0.37
SVL/NL x S/HL,NT	72	1728.34	
SHC x NL	3	5311.40	33.78***
SHC x NL x HL	6	266.74	0.85
SHC x NL x NT	6	688.65	2.19
SHC x NL x HL x NT	12	447.25	0.71
SHC x NL x S/HL,NT	108	5661.05	
SHC x SVL/NL	6	119.90	0.77
SHC x SVL/NL x HL	12	303.37	0.97
SHC x SVL/NL x NT	12	193.63	0.62
SHC x SVL/NL x HL x NT	24	390.69	0.63
SHC x SVL/NL x S/HL,NT	216	5608.57	
Total	719	84689.67	

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

correctly identified (written) phonemes. The total possible score on any word list trial was 90, or 3 phonemes per each of 30 isophonemic consonant-vowel-consonant CVC words. For each experimental treatment, the number correct out of 90 was converted to a percentage score. (Therefore, in each of the ensuing tables and figures the mean scores represent the percentage of correctly identified phonemes.)

The ANOVA revealed significance for all main effects with the exception of subject's hearing level blocks. Significant interactions included: subject's hearing configuration-by-hearing level, noise level-by-hearing level, noise level-by-noise spectral type, speaker voice level nested within noise level-by-noise spectral type, and subject's hearing configuration-by-noise level. The only third or higher order interaction to approach significance was subject's hearing configuration-by-noise level-by-noise type, $F\ (6,\ 108) = 2.19$, $p = 0.05$. However, due to the fact that the practical significance of the interaction is difficult to interpret, it was not subjected to further analysis.

Next, these significant effects were analyzed in detail, including multiple-range mean comparisons, as discussed in the subsequent sections. Interactions are discussed first followed by main effects. Due to the difficulty in interpreting interactions, in all cases, the data means were first plotted and then Newman-Keuls tests were applied to the data to determine the loci of significance. It is stressed that all results and ensuing discussions are based on the sample data collected during this experimental investigation and only statistically-significant differences (at $p < .05$) are presented. Generalizations derived from these results should be made judiciously and in the context of the experimental conditions described herein. There are many confounding factors present in industrial settings which may result in different speech reception/discrimination performances from those obtained in a controlled study.

Subject Hearing Configuration-by-Hearing Level Interaction

The significant SHC by HL interaction, F (6, 108) = 2.74, p = 0.0163, yielded two arrangements which were amenable to further analysis. The differences between HPDs for each hearing level could be analyzed, as could the differences between each hearing level for a given HPD. The latter arrangement was of less interest, however, in the interest of completeness the Newman-Keuls test was applied and the results are shown in Table 2. In this arrangement, the only significance appeared between the moderate hearing loss condition and the normal, slight conditions for earplugs alone.

The analysis concerning the differences between hearing configurations for each hearing level revealed significant differences only under the moderate hearing loss category (Table 3). Here, the subjects with the poorest hearing in the study were most hindered by the earplug (the HPD with the maximum NRR). Discrimination scores were significantly worse with the earplug than with either the unoccluded condition or the earcap. This is illustrated by the graphs of the mean scores in Figure 10. There were no significant differences among subject hearing configurations under the normal and slight loss categories.

It can be concluded from this interaction that HPDs with large NRRs may reduce speech reception and discrimination for subjects with moderate hearing loss more than for subjects with little or no hearing loss. Of course, these results were collapsed across the ambient noise conditions in the study.

Table 2

Newman-Keuls Test for the Subject Hearing Configuration-by-Hearing Level Interaction -- Hearing Level Differences as a Function of Subject Hearing Configuration

Alpha Level = 0.05 dF = 108 MSE = 67.25 n = 60

Mean % Correct	Hearing Level	Code*
Unoccluded Condition		
83.03	slight loss	A
82.74	moderate loss	A
81.98	normal hearing	A
Earcap Condition		
84.17	slight loss	A
81.42	moderate loss	A
80.54	normal hearing	A
Earmuff Condition		
81.80	slight loss	A
81.59	normal hearing	A
78.54	moderate loss	A
Earplug Condition		
82.16	normal hearing	A
80.90	slight loss	A
76.22	moderate loss	B

* means within a SHC condition with the same letter are not significantly different at $p < 0.05$

Table 3

Newman-Keuls Test for the Subject Hearing Configuration-by-Hearing Level Interaction -- Hearing Configuration Differences as a Function of Hearing Level

Alpha Level = 0.05 dF = 108 MSE = 67.25 n = 60

Mean % Correct	Subject Hearing Configuration	Code*	
Normal Hearing			
82.16	earplug	A	
81.98	unoccluded	A	
81.59	earmuff	A	
80.54	earcap	A	
Slight Loss			
84.17	earcap	A	
83.03	unoccluded	A	
81.80	earmuff	A	
80.90	earplug	A	
Moderate Loss			
82.74	unoccluded	A	
81.42	earcap	A	
78.54	earmuff	A	B
76.22	earplug		B

* means within a HL condition with the same letter are not significantly different at $p < 0.05$

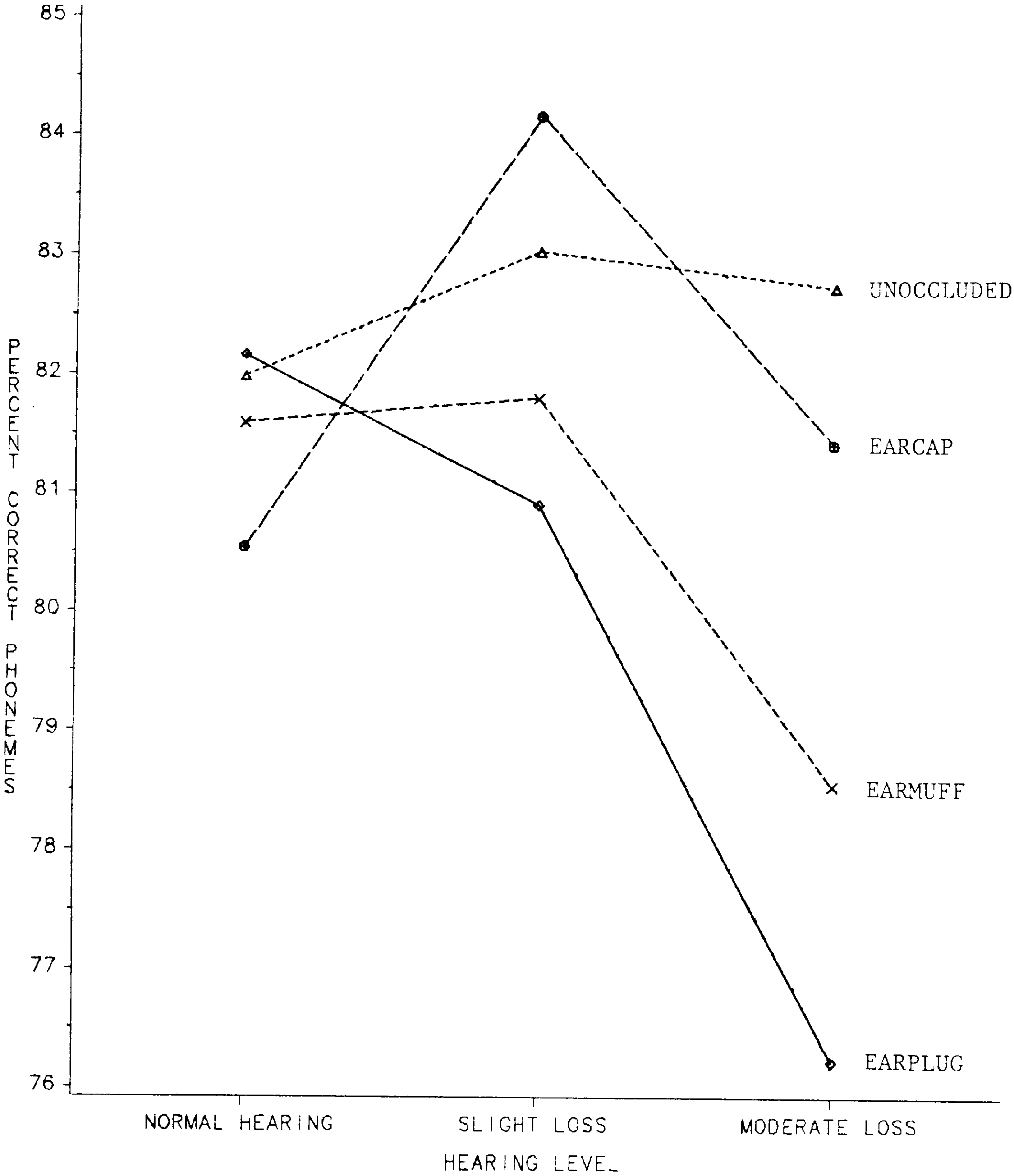

Figure 10. Subject hearing configuration as a function of subject hearing level.

Ambient Noise Level-by-Subject Hearing Level Interaction

The interaction of ambient noise level-by-subject hearing level was significant F (2, 36) = 3.43, p = 0.0434. A Newman-Keuls test was conducted for all of the treatment means contained in the two arrangements of the interaction. The results of the tests are shown in Tables 4 and 5 and graphed in Figure 11. The results in Table 4 and Figure 11 show that for the subject groups having normal hearing or a slight loss, the reception/discrimination mean performance scores were significantly higher in the 60 dBA ambient noise level when compared with the 83 dBA ambient noise level. For the moderate hearing loss group, there was no difference in mean performance scores achieved in the 60 and 83 dBA ambient noise levels.

The results in Table 5 reveal that for the 60 dBA ambient noise level, subjects having a moderate degree of hearing loss achieved significantly lower reception/discrimination scores when compared to normal hearing and slight hearing loss subjects. The normal hearing and slight hearing loss groups did not differ in performance scores for the 60 dBA ambient noise level nor did any of the subject groups differ in the 83 dBA ambient noise.

Table 4

Newman-Keuls Test for the Ambient Noise Level-by-Subject Hearing Level -- Ambient Noise Level Effects as a Function of Hearing Level

Alpha Level = 0.05	dF = 36	MSE = 64.83	n = 120

Mean % Correct	Ambient Noise Level	Code*
Normal Hearing		
84.70	60 dBA	A
78.43	83 dBA	B
Slight Loss		
84.58	60 dBA	A
80.37	83 dBA	B
Moderate Loss		
80.94	60 dBA	A
78.52	83 dBA	A

* means within a HL condition with the same letter are not significantly different at $p < 0.05$

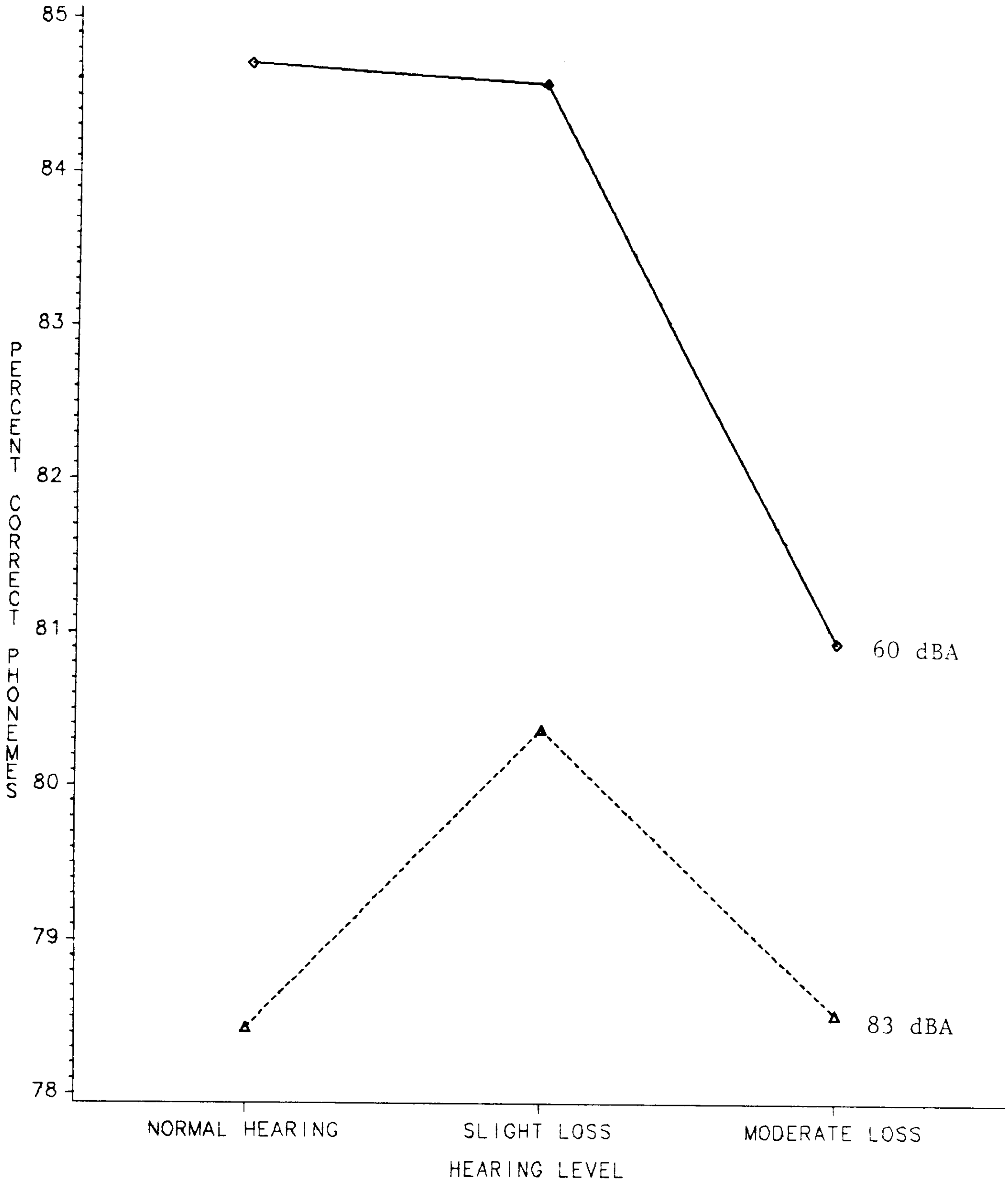

Figure 11. Ambient noise level effects on discrimination as a function of hearing level.

Table 5

Newman-Keuls Test for the Ambient Noise Level-by-Subject Hearing Level -- Hearing Level Differences as a Function of Ambient Noise Level

Alpha Level = 0.05	dF = 36	MSE = 64.83	n = 120

Mean % Correct	Hearing Level	Code*
60 dBA Ambient Noise Level		
84.70	normal hearing	A
84.58	slight loss	A
80.94	moderate loss	B
83 dBA Ambient Noise Level		
80.37	slight loss	A
78.52	moderate loss	A
78.43	normal hearing	A

* means within a NL condition with the same letter are not significantly different at $p < 0.05$

Ambient Noise Level-by-Ambient Noise Spectral Type Interaction

The two-way interaction of ambient noise level-by-ambient noise spectral type was significant, F (2, 36) = 18.85, p = 0.0001. Tables 6 and 7 show the results of the Newman-Keuls tests on the two different arrangements of the mean interactions. In Table 6 and Figure 12, the effects of ambient noise spectral type as a function of ambient noise level are shown. For the 60 dBA ambient noise level condition, subjects in the high and white spectral noise types achieved significantly higher scores than did those subjects in the low frequency noise type. The performance scores between groups in the high and white noise types were not significant at 60 dBA. For the 83 dBA ambient noise level condition, the high frequency noise resulted in the best reception/discrimination scores followed by the white noise approximation. The lowest scores occurred with the low frequency noise spectral type, perhaps because this noise produced the most upward masking of the male speech spectrum.

A Newman-Keuls comparison of the two noise levels used (60 and 83 dBA) as a function of each of the spectral noise types appears in Table 7. Significant differences in mean phoneme scores occurred between the 60 and 83 dBA noise levels in the low frequency and white spectral noise types. That is, mean scores were higher at the lower noise level. However, in the high frequency spectral noise type, the noise levels did not result in significantly different scores. The high frequency noise masking effect evidently did not intrude heavily on the critical speech bandwidth.

Table 6

Newman-Keuls Test for the Ambient Noise Level-by-Ambient Noise Spectral Type Interaction -- Noise Type Effects as a Function of Noise Level

Alpha Level = 0.05   dF = 36   MSE = 64.83   n = 120

Mean % Correct	Ambient Noise Spectral Type	Code*
60 dBA Ambient Noise Level		
86.28	high frequency	A
85.12	white approximation	A
78.83	low frequency	B
83 dBA Ambient Noise Level		
87.19	high frequency	A
78.24	white approximation	B
71.90	low frequency	C

* means within a NL condition with the same letter are not significantly different at $p < 0.05$

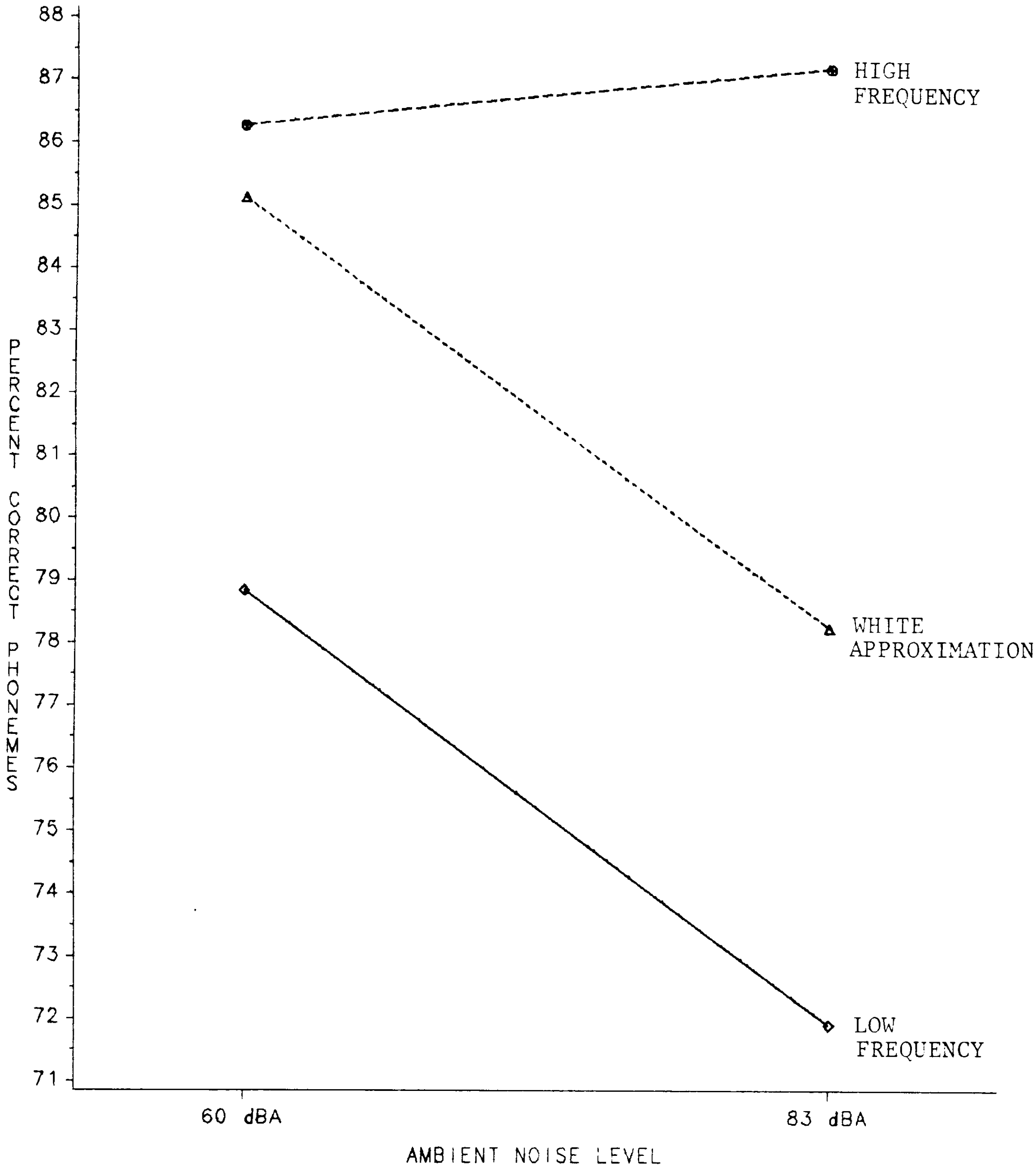

Figure 12. Ambient noise spectral type effects as a function of ambient noise level.

Table 7

Newman-Keuls Test for the Ambient Noise Level-by-Ambient Noise Spectral Type Interaction -- Noise Level Effects as a Function of Noise Type

Alpha Level = 0.05 dF = 36 MSE = 64.83 n = 120

Mean % Correct	Ambient Noise Level	Code*
Low Frequency Noise		
78.83	60 dBA	A
71.90	83 dBA	B
White Noise Approximation		
85.12	60 dBA	A
78.24	83 dBA	B
High Frequency Noise		
87.19	83 dBA	A
86.28	60 dBA	A

* means within a NT condition with the same letter are not significantly different at $p < 0.05$

Subject Hearing Configuration-by-Ambient Noise Level Interaction

The interaction of subject hearing configuration-by-ambient noise level was significant, F (3, 108) = 33.78, p = 0.0001 and the subsequent multiple-comparisons analyses revealed several important effects.

In Table 8, a comparison of the 60 and 83 dBA noise levels at each of the listener's hearing configurations is shown. For the unoccluded and earcap conditions, the reception/discrimination scores achieved in the 60 dBA noise level were significantly higher than those achieved in the 83 dBA noise level. The earcap had the lowest NRR (17 dB) of any of the HPDs tested. In the earplug condition (NRR = 29 dB), the reception/discrimination scores achieved in the 83 dBA noise level were significantly greater than those achieved in the 60 dBA noise level. Finally, for the earmuff condition, reception/discrimination mean scores did not significantly differ between 60 and 83 dBA ambient noise levels. These results are illustrated in Figure 13.

In Table 9, a comparison of the listener hearing configurations at each of the two noise levels is shown. At the 60 dBA noise level, the unoccluded and earcap conditions resulted in the highest reception/discrimination scores. The next highest scores were achieved in the earmuff condition followed by the earplug condition. The earplug had the highest NRR (29 dB) of the group and it also yielded the maximum degradation of reception/discrimination performance in low (60 dBA) ambient noise level. Again, these results are depicted in Figure 14.

Table 8

Newman-Keuls Test for the Subject Hearing Configuration-by-Ambient Noise Level Interaction -- Ambient Noise Level Effects as a Function of Subject Hearing Configuration

Alpha Level = 0.05 dF = 108 MSE = 52.42 n = 90

Mean % Correct	Ambient Noise Level	Code*
Unoccluded Condition		
88.00	60 dBA	A
77.16	83 dBA	B
Earcap Condition		
86.05	60 dBA	A
78.03	83 dBA	B
Earmuff Condition		
81.29	60 dBA	A
80.00	83 dBA	A
Earplug Condition		
81.23	83 dBA	A
78.29	60 dBA	B

* means within a SHC condition with the same letter are not significantly different at $p < 0.05$

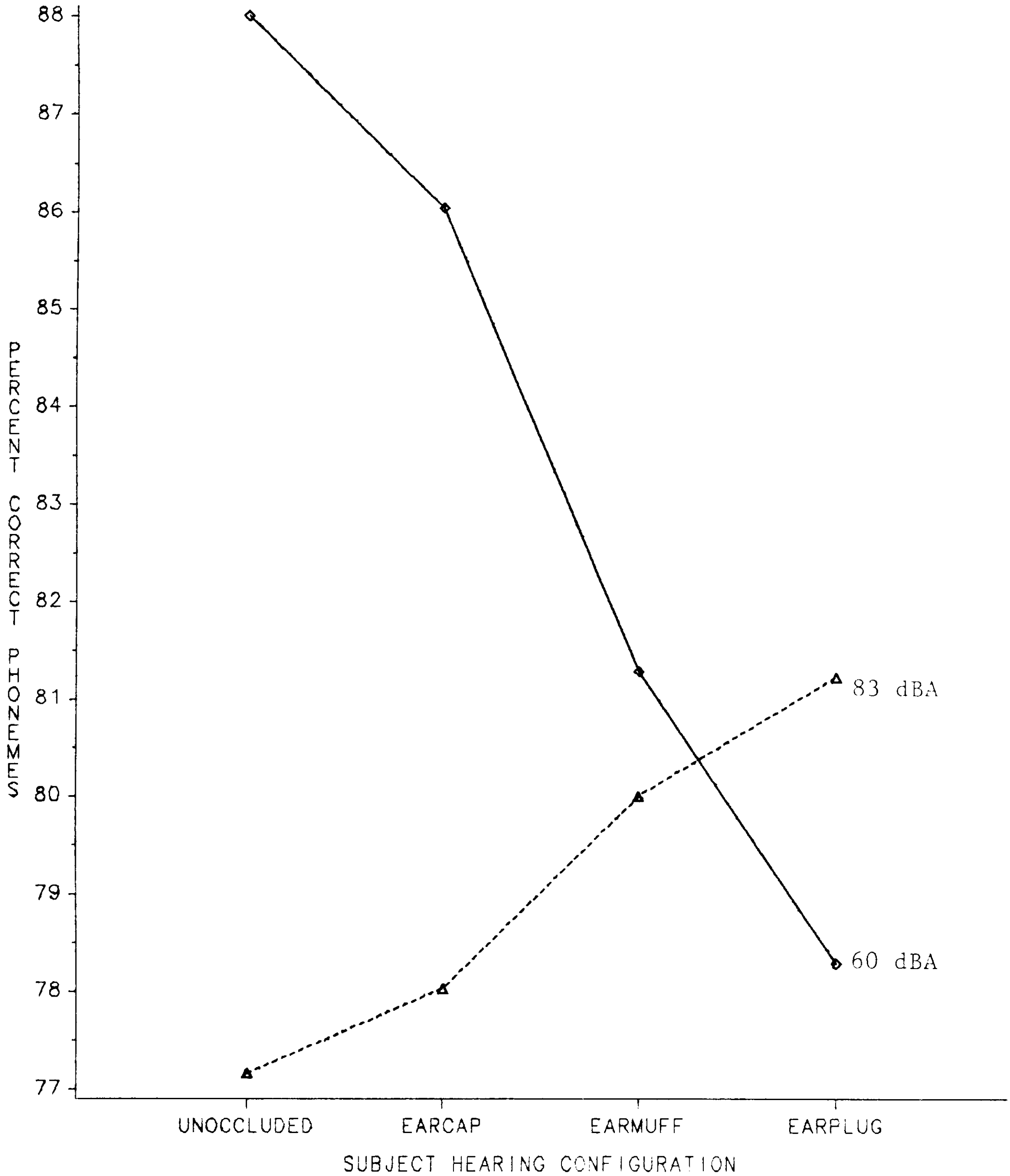

Figure 13. Ambient noise level effects as a function of subject hearing configuration.

Table 9

Newman-Keuls Test for the Subject Hearing Configuration-by-Ambient Noise Level Interaction -- Hearing Configuration Effects as a Function of Noise Level

Alpha Level = 0.05 dF = 108 MSE = 52.42 n = 90

Mean % Correct	Subject Hearing Configuration	Code*
60 dBA Ambient Noise Level		
88.00	unoccluded	A
86.05	earcap	A
81.29	earmuff	B
78.29	earplug	C
83 dBA Ambient Noise Level		
81.23	earplug	A
80.00	earmuff	A B
78.03	earcap	B
77.16	unoccluded	B

* means within a NL condition with the same letter are not significantly different at $p < 0.05$

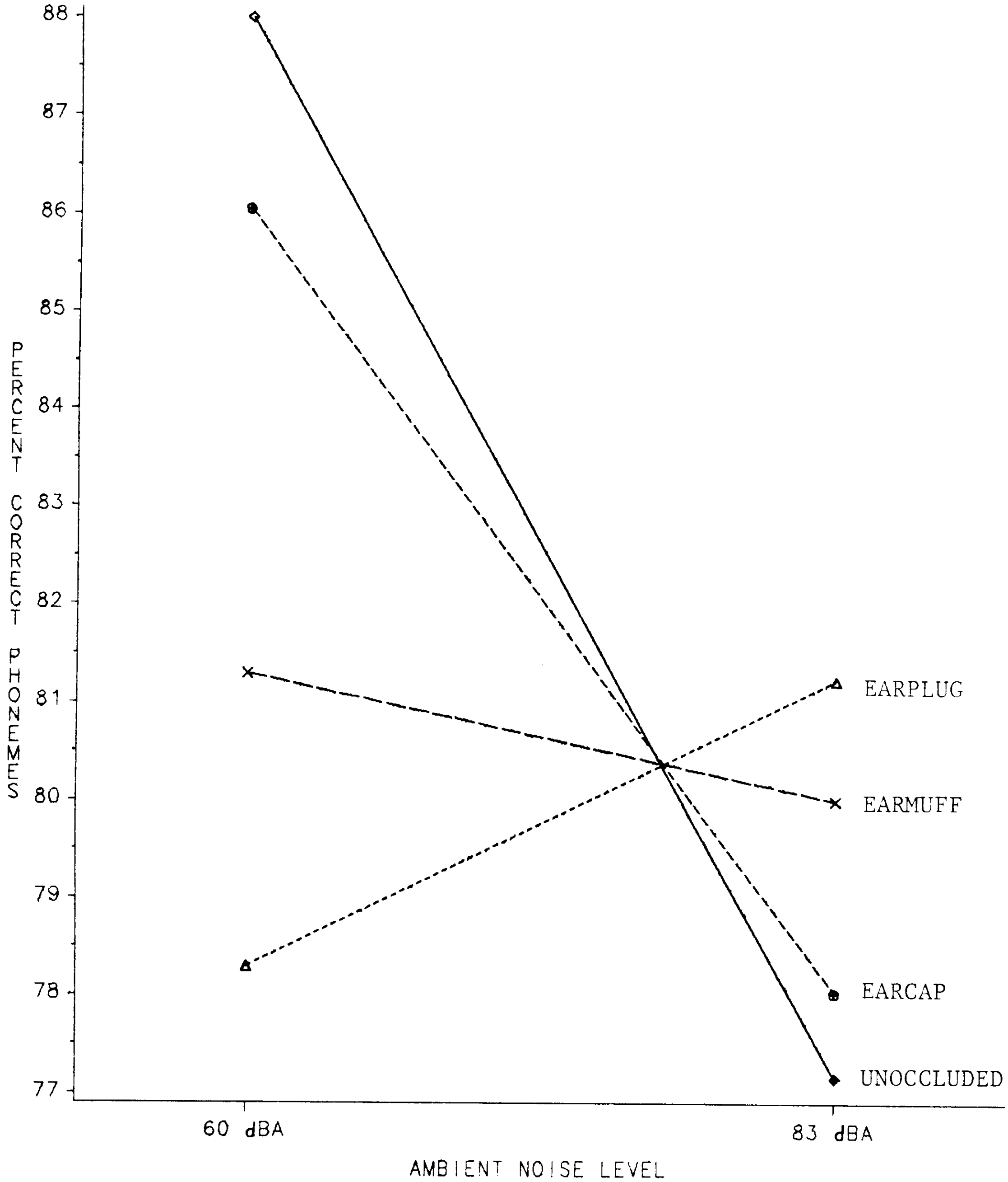

Figure 14. Subject hearing configuration effects as a function of ambient noise level (replotting of Figure 13 data).

For the 83 dBA ambient noise level, the results (Table 9) show that the use of earplugs resulted in significantly higher speech reception/discrimination scores when compared to earcaps and the unoccluded condition but was not significantly different than the earmuff condition. In turn, the earmuff condition was not significantly different than the earcap or unoccluded condition.

Note that the earplug, while degrading speech discrimination (compared to unoccluded) in the low level ambient, actually enhanced discrimination (compared to unoccluded) in the high level ambient. Therefore, the highest NRR protector (earplugs) may have "overprotected" in 60 dBA in that speech discrimination suffered, (and of course protection would not be needed at that level anyway), but it provided maximal speech reception at high ambient levels. The other protectors did not provide enhanced detection over the unoccluded condition.

Speaker Voice Level (Nested Within Noise Level)-by-Ambient Noise Spectral Type

This interaction was significant at F (4, 72) = 26.00, p = 0.0001. The breakdown of this effect was somewhat difficult to interpret due to the nesting of speaker voice level within ambient noise level to simulate Lombard effects on the speaker. However, the Newman-Keuls analysis of the effect of noise spectral type as a function of speaker voice level revealed some trends which can be interpreted.

Table 10 provides the phoneme mean scores for each ambient noise type under each speaker presentation voice level. For each voice level, the ordering of means for noise types was consistent, though the statistically-significant differences varied. At the 83 dBA ambient noise level, regardless of the speaker's voice level, the masking decrement provided by low frequency noise was greatest, followed by white noise approximation, and lastly by high frequency noise. That is, high frequency noise was least interfering while low frequency was most interfering. This trend was also evident for the 60 dBA noise level, again regardless of speaker voice level, although the differences between the high and white noise effects were nonsignificant at $p < 0.05$. However, low frequency noise again provided significantly greater masking effects at the low ambient noise levels as well as at the high noise levels. These effects are depicted in the mean plots of Figure 15.

Table 10

Newman-Keuls Test for Ambient Noise Spectral Type-by-Speaker's Voice Level (Nested Within Ambient Noise Level)

Alpha Level = 0.05 dF = 72 MSE = 24.00 n = 60

Mean % Corrected	Ambient Noise Spectral Type	Code*
Speaker's Voice Level at 63 dBA (in 60 dBA Noise Level)		
85.19	high frequency	A
84.69	white approximation	A
77.89	low frequency	B
Speaker's Voice Level at 65 dBA (in 60 dBA Noise Level)		
87.37	high frequency	A
85.55	white approximation	A
79.76	low frequency	B
Speaker's Voice Level at 82 dBA (in 83 dBA Noise Level		
84.06	high frequency	A
70.44	white approximation	B
62.63	low frequency	C
Speaker's Voice Level at 88 dBA (in 83 dBA Noise Level)		
90.31	high frequency	A
86.03	white approximation	B
81.17	low frequency	C

* means within a SVL condition with the same letter are not significantly different at $p < 0.05$

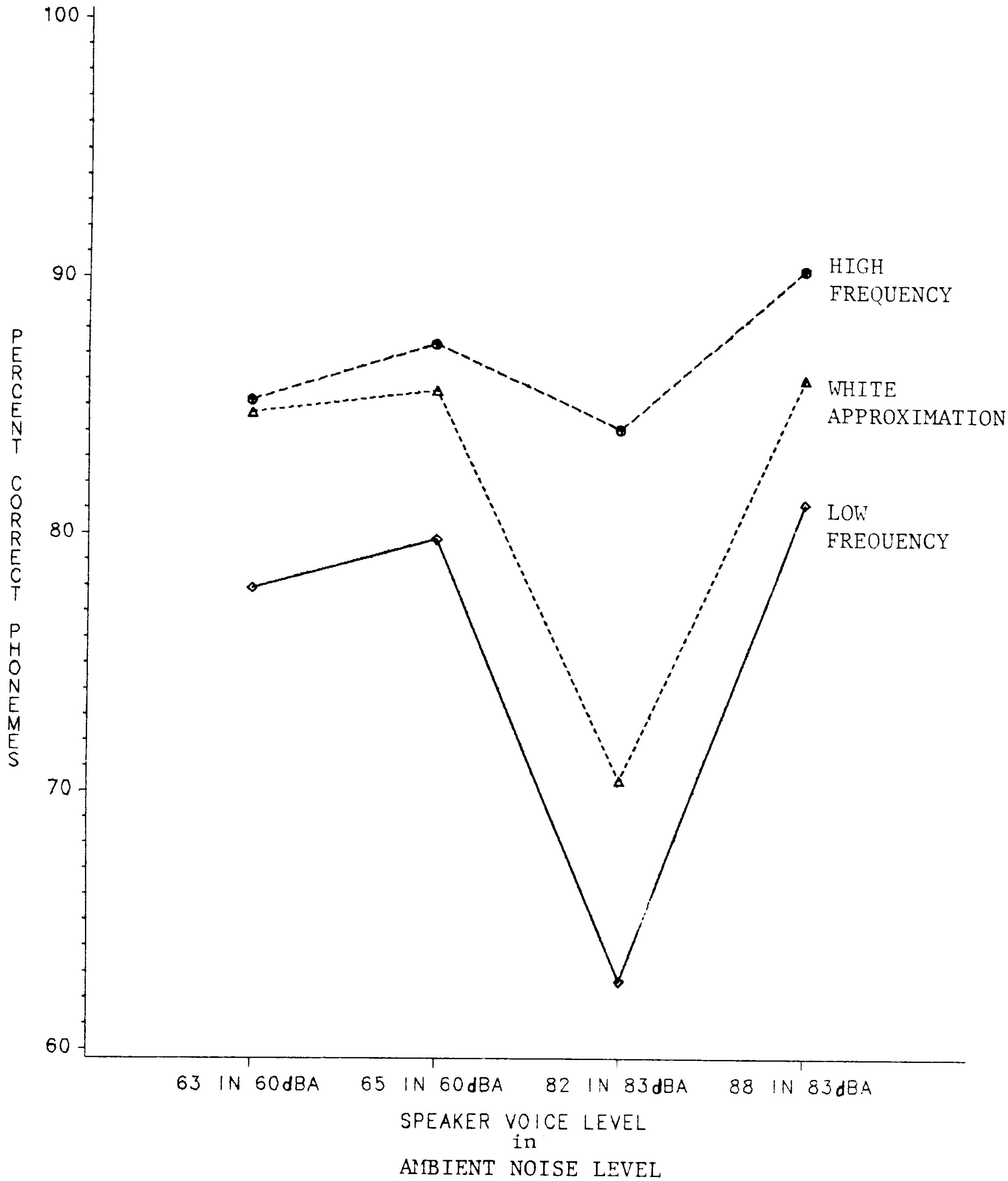

Figure 15. Ambient noise spectral type effects as a function of speaker's voice level nested within ambient noise level.

Hearing Level Blocks

As mentioned at the outset of the results section, all main effects, with the exception of subject hearing level blocks, demonstrated a significant influence on word discrimination ($p < 0.01$). In the case of subject hearing level, there would have likely been a main effect had a wide range of hearing levels been investigated. However, hearing level was used as a blocking variable only, to control for inter-individual differences. As will be recalled, the blocks consisted of "normal" hearing (mean range of -1.9 dBHL to 3.5 dBHL), "slight" loss (mean range of 3.9 dBHL to 6.7 dBHL), and "moderate" loss (mean range of 6.9 dBHL to 23.4 dBHL). These blocks were obtained from the continuum of university subjects qualifying for the study and none of the subjects demonstrated profound loss. Despite the lack of significance of a main effect of hearing level blocks, it was involved in a significant interaction with subject hearing configuration, as previously discussed.

In the following discussion, the results of the post-hoc tests on each significant main effect are presented. Because each of these main effects was included in at least one significant two-way interaction, their interpretation should be made in light of the appropriate interaction.

Subject Hearing Configuration Main Effect

The main effect of occlusion was significant, $F = (3, 108) = 4.45$, $p = 0.0056$. A Newman-Keuls test conducted to determine the specific location of the four treatment mean differences is shown in Table 11 and Figure 16. The hearing configurations of unoccluded, earcap, and earmuff resulted in superior reception/discrimination scores when compared to the earplug condition. No differences in performance scores were achieved between unoccluded, earcap, and earmuff. The earplug condition, however, resulted in an inferior reception/discrimination performance when compared to the unoccluded and earcap condition, but resulted in no difference in performance when compared to the earmuff condition.

Again, it is important to restrict interpretation of this main effect to the interaction results of hearing configuration with noise level, discussed previously. Though the main effect results indicated that the earplug provided the most hindrance to speech discrimination, the interaction results revealed that the earplug actually enhanced discrimination at the high ambient noise level.

Table 11

Newman-Keuls Test for the Main Effect of Subject Hearing Configuration

Alpha Level = 0.05 dF = 108 MSE = 67.25 n = 180

Mean	Hearing Configuration	Code*	
82.58	unoccluded	A	
82.04	earcap	A	
80.64	earmuff	A	B
79.76	earplug		B

* means with the same letter are not significantly different at $p < 0.05$

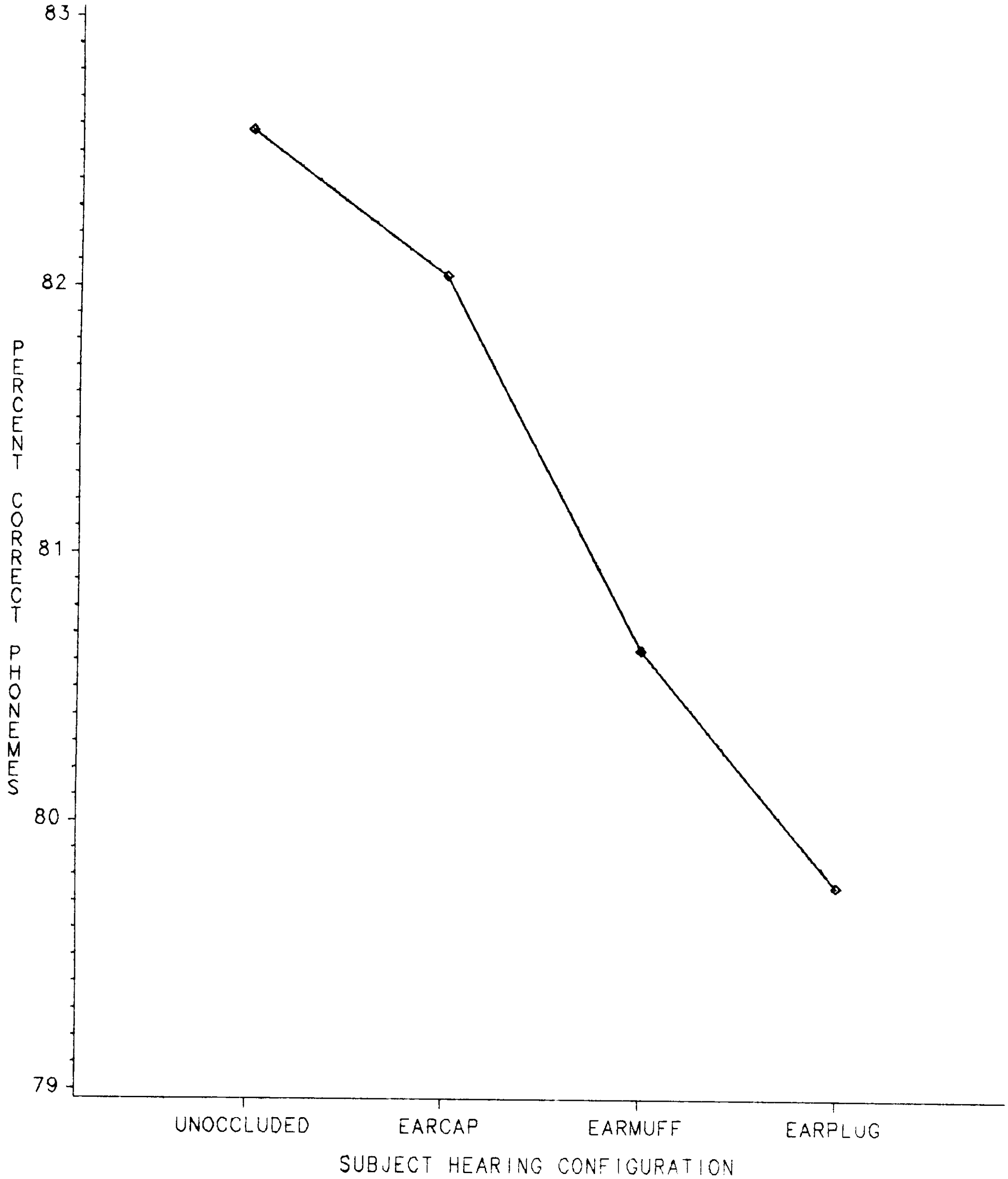

Figure 16. Main effect of subject hearing configuration on speech discrimination.

Ambient Noise Level Main Effect

As expected, there was a strong main effect of ambient noise level on speech discrimination performance as revealed by the overall ANOVA, F (1, 36) = 51.36, p = 0.0001. As shown in Table 12 and Figure 17, the high ambient noise level (83 dBA) resulted in significantly poorer discrimination than the low ambient level (60 dBA). Because there were only two levels of this variable, a post-hoc test was not necessary, therefore the ANOVA main effect results and corresponding means are presented in Table 12. Strict interpretation of the main effect of noise level should be limited to its inclusion in the significant interactions with hearing level blocks, noise type, and speaker hearing configuration, all discussed previously.

Table 12

Main Effect of Ambient Noise Level

Alpha Level = 0.05	dF = 36	MSE = 64.83	n = 360
Mean	Noise Level	Code*	
83.41	60 dBA	A	
79.11	83 dBA	B	

* means with the same letter are not significantly different at $p <$ 0.0001 (from the overall ANOVA in Table 1).

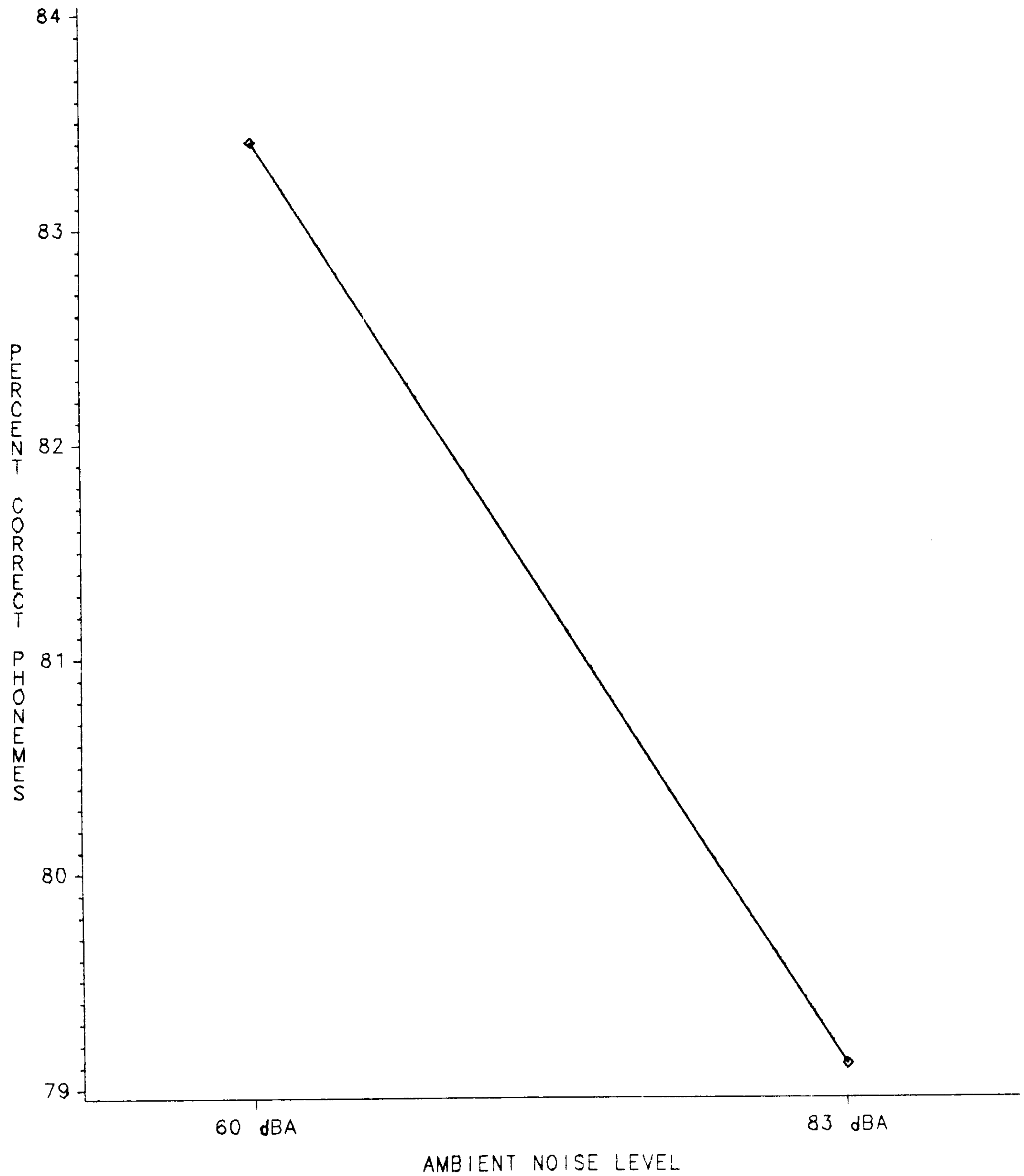

Figure 17. Main effect of ambient noise level on speech discrimination (speech level nested within ambient noise level - see Figure 1).

Ambient Noise Spectral Type Main Effect

The masking effect of noise on speech discrimination performance depended upon the type of noise spectrum presented, as evidenced by the main effect of noise type, F (2, 36) = 32.65, p = 0.0001. The post-hoc test results indicated that low frequency noise provided the most disruption, followed by the approximation of white noise, and then the high frequency noise (Table 13, Figure 18). These results are generally consistent with those involving noise type in an interaction (noise type-by-noise level and noise level-by-speaker voice level) as discussed earlier. In all cases, the low frequency spectrum proved to be the most effective masker of the male speech signal, regardless of the subject's hearing configuration.

Table 13

Newman-Keuls Test for the Main Effect of Ambient Noise Spectral Type

Alpha Level = 0.05	dF = 36	MSE = 238.58	n = 240

Mean	Noise Type	Code*
86.73	High frequency	A
81.68	White approximation	B
75.36	Low frequency	C

* means with the same letter are not significantly different at $p < 0.05$

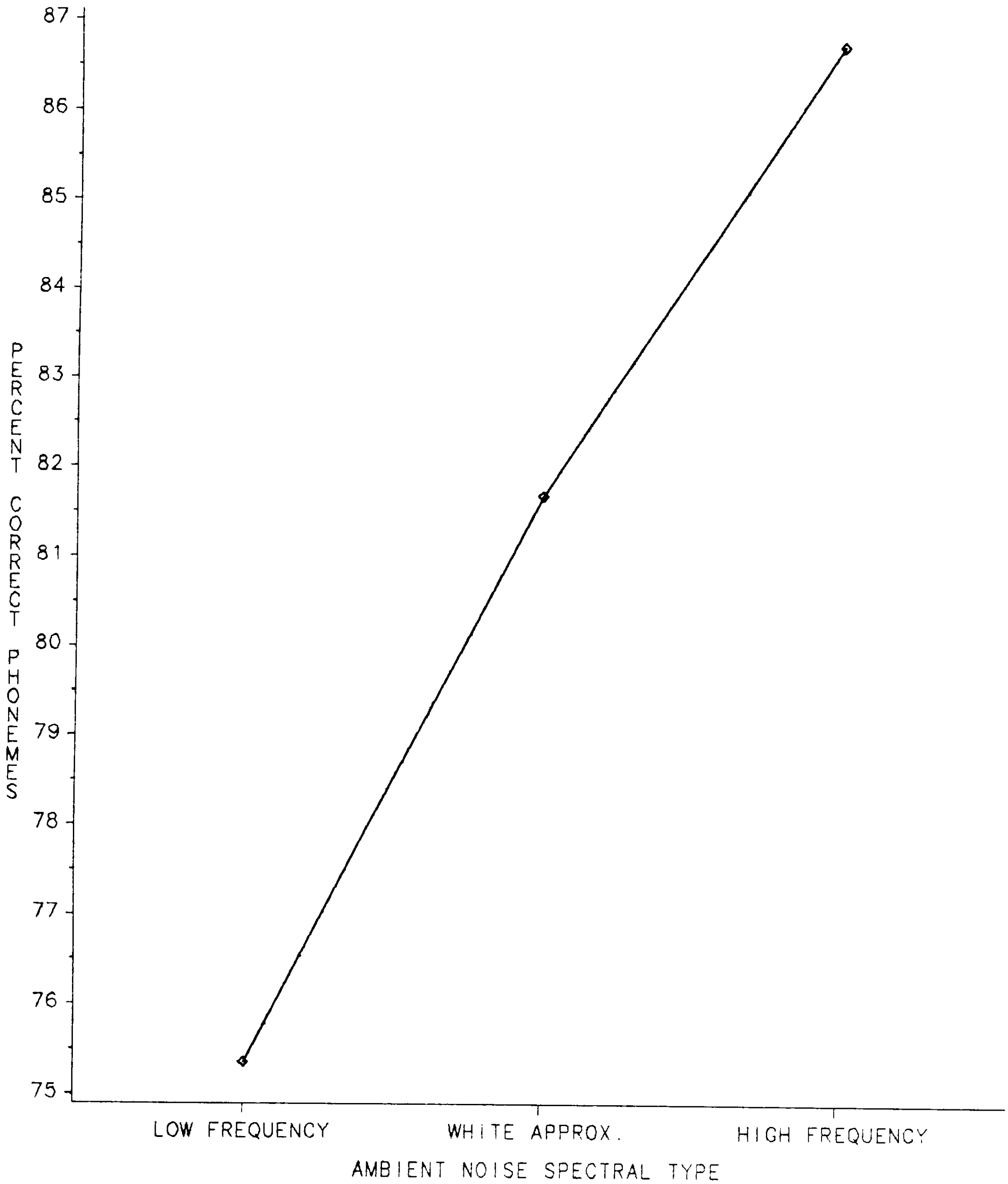

Figure 18. Main effect of ambient noise spectral type on speech discrimination.

<u>Speaker Voice Level Main Effect</u>

As discussed in Appendix B, the voice presentation levels were set for each ambient noise level condition on the basis of a pilot study. This resulted in a nested variable of voice level within noise level. So the interpretation of this variable must be performed with caution. (Speaker voice level was not a factor of prime interest in this effort, therefore the decision to use voice levels as influenced by a speaker Lombard occlusion effect, rather than "artificial" S/N ratios, was made.) The main effect of speaker voice level was highly significant, $F\ (2,\ 72) = 344.70$, $p < 0.0001$. A Newman-Keuls test revealed significance among all speaker voice levels (Table 14, Figure 19). Of most importance is the effect of occlusion (on the speaker's voice level) and its influence on speech discrimination performance. For the high level ambient condition, when the speaker-unoccluded voice level (88 dBA) was presented, speech discrimination performance increased by approximately 13% over the speaker-occluded voice level (82 dBA), a statistically-significant difference. For the low level ambient condition, when the speaker-unoccluded voice level (65 dBA) was presented, speech discrimination performance increased by approximately 2% over the speaker-occluded voice level (63 dBA), a much smaller effect though still statistically-significant. In the high intensity ambient, it is quite possible that cochlear distortion occurred and the S/N ratio increase (from speaker-occluded level to speaker-unoccluded level) resulted in the larger increase in discrimination over that yielded in the relatively quiet 60 dBA ambient condition. Again, note

Table 14

Newman-Keuls Test for the Main Effect of Speaker Voice Level (Nested Within Noise Level)

Alpha Level = 0.05	dF = 72	MSE = 24.00	n = 180

Mean	Voice Level	(nested within) Noise Level	Code*
85.84	88 dBA	83 dBA	A
84.23	65 dBA	60 dBA	B
82.59	63 dBA	60 dBA	C
72.38	82 dBA	83 dBA	D

* means with the same letter are not significantly different at $p < 0.05$

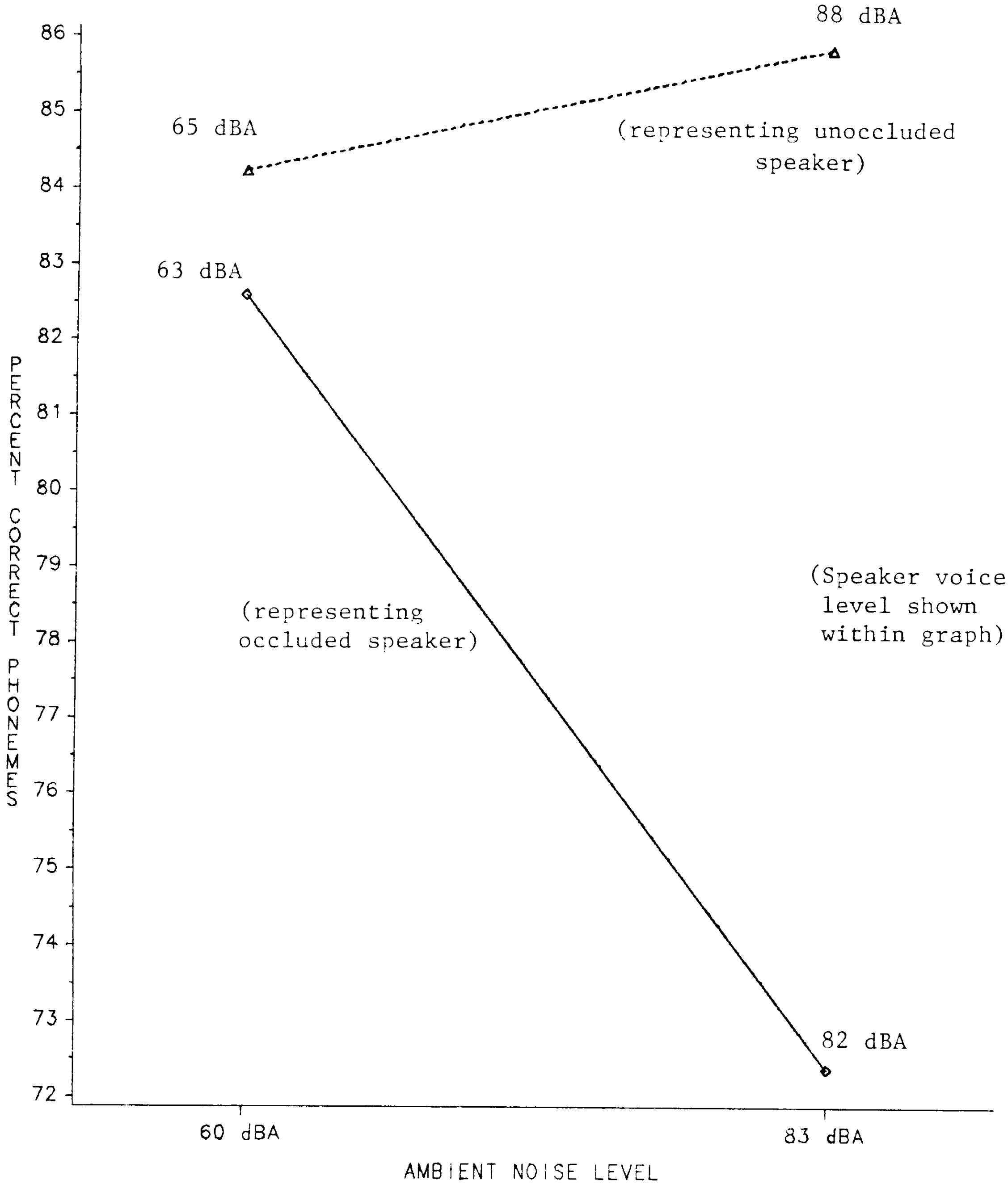

Figure 19. Main effect of speaker's voice level (nested within ambient noise level) on speech discrimination.

that for the voice level conditions representing an unoccluded speaker, the S/N ratio was set at +5 at both 60 and 83 dBA ambient noise levels. Therefore, these two conditions were directly comparable from a strict S/N ratio standpoint. (The actual difference between performance in the 88 dBA voice/83 dBA ambient and the 65 dBA voice/60 dBA ambient was significant, though numerically (practically) very slight at 1.5%.) The Lombard occlusion effect determined in the pilot study for both ambient conditions was more pronounced at the higher noise level than at the low level. Therein lies the fundamental reason for "nesting" speaker voice level within ambient noise level.

DISCUSSION AND CONCLUSIONS

The goals of the research project described herein were met. That is, a successful evaluation of the effects of hearing protection and related industrial factors on the reception and discrimination of spoken words was completed. A discussion of the primary findings follows.

Hearing Level (Blocks) Conclusions

As evidenced by the lack of a main effect of hearing level blocks (Table 1), there were no significant differences among hearing levels with respect to speech reception/discrimination performance. However, it is emphasized that a larger dispersion of hearing levels would likely have demonstrated an effect. The present study was not an investigation of hearing level per se, rather, hearing level was used as a blocking variable. This was to minimize between-subjects differences so that the effects of the variables of primary interest would not be clouded by differences in subjects' hearing acuities. Recalling that the hearing level blocks included mean thresholds across frequency of -1.9 dBHL to 3.5 dBHL (normal hearing), 3.9 dBHL to 6.7 dBHL (slight loss), and 6.9 dBHL to 23.4 dBHL (moderate loss), it is evident that severely-impaired subjects were not part of the sample. Therefore, the subjects represented a fairly homogeneous group and any hearing level differences within that group were controlled for via the blocking scheme.

When interacting with the independent variables of subject hearing configuration and ambient noise level, the hearing level block is important to consider because of the significance of the interactions. These effects are discussed next in the context of the primary independent variables.

Subject Hearing Configuration Conclusions

Hearing configuration main effect. The strong main effect of subject hearing configuration suggests that there are differences among the effects of unoccluded conditions and various HPD-occluded conditions on speech discrimination. No differences in performance were found between the unoccluded, earcap, and earmuff conditions, suggesting that when the data were collapsed across other variables, there were no differences in the effects of these hearing protection devices on discrimination. However, the high attenuation earplug (NRR = 29 dB) yielded speech discrimination scores which ranked lowest of all HPDs, though the difference between earplug and earmuff was nonsignificant. It is critical, however, to interpret this effect in light of the interaction of subject hearing configuration with noise level and with hearing level blocks.

Interaction with noise level. First, the highest attenuating HPD (the earplug) resulted in the best speech discrimination in the high noise level at a S/N ratio of 5 dB, for which it was significantly better than the earcaps and the unoccluded condition. (This, of course, was not apparent in the examination of the main effect of subject hearing configuration alone.) Due to their high attenuation capabilities, both the earmuff and earplug produced the lowest speech discrimination scores in the low (60 dBA) ambient noise level. However, their increased protection would not be needed at this level. One may conclude that the more protective (higher NRR) HPDs may not only be better at high noise levels from a hearing conservation standpoint, but also enhance speech discrimination as well. However, "overprotection" at lower ambient noise levels may degrade communication performance. On the other hand, both the unoccluded and low-attenuation earcap (NRR=17 dB) conditions produced the highest speech discrimination at the low ambient noise level but speech discrimination worsened considerably in the high ambient noise (Table 8). This suggests that low HPD attenuation at high ambient levels may result in inadequate ear protection as well as non-optimal speech intelligibility.

Interaction with hearing level. When considering the combined effects of subject hearing configuration and hearing level block, several trends are apparent. First, for all hearing configurations except earplugs, there were no differences among hearing level blocks with respect to speech discrimination. Thus, this was consistent with the lack of a block main effect, except that earplug users did have significantly poorer discrimination abilities if they were of the "moderate" hearing loss group (Table 2). Furthermore, when the discrimination data were collapsed across the ambient noise conditions in the study, the subjects possessing the poorest hearing had the most difficulty with word discrimination when wearing the highest-attenuating HPDs (the earmuff and earplug). The hearing configuration for normal hearers and those with slight loss had no significant overall effect (Table 3).

Coupling these results with the interaction of hearing configuration and hearing level, one may speculate that the earplug and possibly the earmuff (the highest attenuating HPDs) are the most appropriate selections for achieving speech discrimination in high noise levels, provided that the user does not have considerable loss of hearing. (Recall that the S/N ratios may remain the same from a low ambient to high ambient condition, but cochlear distortion in high ambient is greater, therefore, the better HPD is at an advantage at higher levels.) Minimal or no protection in high ambient noise levels may result in a degradation in speech discrimination for both normal and hearing-impaired individuals.

Differences in word discrimination achieved among HPDs at the two ambient noise levels may be explained, in part, by differences in their spectrum of attenuation. Recall that the highest attenuating HPD, the earplug (NRR = 29), was the only device which significantly improved word discrimination in 83 dBA noise over the unoccluded condition -- a difference of approximately 4%. The spectral attenuation of the earplug, as indicated by the manufacturer, is quite high in the low frequency ranges from 125-500 Hz and higher than either the earmuff and earcap at all frequencies except 1000 and 2000 Hz where the earmuff shows a slight advantage (Casali et al., 1985). The earplug's advantage in enhancing speech discrimination at the 83 dBA ambient intensity level may be due, in part, to its strong low frequency attenuation which would have reduced the upward masking effects of low noise frequencies into the critical speech bandwidth. This would be expected to be especially important for the low frequency ambient noise, though a significant hearing configuration-by-noise spectral type interaction did not surface. On the other hand, at 60 dBA ambient levels, where noise masking was not as significant a problem, the earmuff and earplug reduced the speech level to a degree that discrimination was significantly worse than for the unoccluded condition and for the relatively low-attenuating earcap (NRR = 17).

The spectral attenuation of the earcap was considerably lower than that of either the earmuff or earplug, especially at low frequencies and in the speech bandwidth. In the 60 dBA condition, the earcap did not degrade discrimination over the unoccluded condition, however at 83 dBA it offered no advantage either.

It is stressed that in the high noise level condition, <u>none</u> of the HPDs tested degraded speech discrimination over that achieved by an unoccluded listener. Furthermore, the earplug offered the advantage of enhanced discrimination. The lack of HPD degradation may be explained by the fact that an HPD will attenuate equally the different levels of a given frequency of a sound, be they signal or noise in content, and therefore will not change the signal-to-noise ratio from an unoccluded condition. Therefore, theoretically the intelligibility will not change. However, at high sound levels, the attenuation provided by an

HPD may reduce the overall sound (signal plus noise) level to an extent that "cochlear distortion" (e.g., see Lawrence and Yantis, 1956) is significantly reduced from that experienced in an unoccluded condition. If this is the case, speech intelligibility may improve when wearing the HPD because the ear can more favorably manage the signal and noise level inputs. This reduction in distortion may be further complemented by the fact that the HPD may reduce the signal and noise below the threshold of the aural (stapedius) reflex, which is known to reduce sensitivity to sounds of above approximately 80 dB (e.g., Dallos, 1964). Perhaps these aural phenomena provide some physiological support for the advantage in speech discrimination afforded by the earplug in high noise levels.

Ambient Noise Level and Speaker Voice Level Conclusions

Noise level and voice level main effects. The significant main effect of ambient noise (in which speaker voice level was nested) revealed, as expected, that speech discrimination in 60 dBA ambient noise was better than in 83 dBA ambient noise. Collapsed across all other variables, this mean difference represented approximately 4.5% improvement from 83 dBA to 60 dBA for the isophonemic word discrimination task used in this study (Table 12). This main effect was restricted, however, by the interaction with hearing level and noise type.

From an examination of the speaker voice level effect in Table 14 (which must be interpreted in conjunction with noise level in which it was nested), it is apparent that the higher S/N ratios consistently resulted in significantly better word discrimination scores, a fact well-documented in many previous studies. However, with the higher voice level condition, in which S/N ratio was constant at +5 across ambient noise conditions, subjects did slightly better in the high noise condition than in the lower noise condition. This difference of 1.6% is of little practical significance, though statistically-significant in the Newman-Keuls test. It is also difficult to account for in terms of the cochlear distortion hypothesis which would suggest that higher distortion would occur at higher noise levels, decreasing intelligibility at those levels. However, it must be noted that the voice level effect in this study was collapsed across noise type, hearing level, and hearing configuration. Furthermore, its interactive effect with noise type was significant. Therefore, the voice level influence could not be reduced to a pure main effect in its interpretation. In any event, this effect should be considered to be of little practical significance due to the small mean difference revealed.

Of considerably more importance is the impact of the Lombard occlusion effect on speaker voice level, under each noise level, on discrimination performance. Recall that in the pilot study, subjects demonstrated an average occlusion effect of 6 dBA in the high ambient noise level and 2 dBA in the low ambient noise level. The reproduction (during the experiment) of the Lombard reduction in speaker voice level in the high intensity ambient conditions resulted in a mean decrease in discrimination performance of approximately 13.5%. For the low intensity ambient conditions, the Lombard effect resulted in a mean decrease of approximately 1.6% in discrimination. (Both of these decreases were statistically-significant at $p < 0.05$.) This finding suggests that the Lombard occlusion effect must be carefully considered in any study of this type because of its influence on speaker voice level, and therefore on S/N ratio in the noise environment. It also is clear from the pilot study results that the reduction in voice level due to occlusion is more pronounced in the high ambient noise environment.

Interaction of noise level with subject hearing level block. As earlier stated, hearing level blocks did not significantly influence word discrimination in this study, perhaps due to the relatively small dispersion of hearing levels used. However, when combining hearing level with noise level, there was a significant trend. Subjects in the normal and slight loss categories demonstrated significant degradations in word discrimination performance from the 60 dBA noise level to 83 dBA level (Table 4). This was not true for the moderate hearing loss category; those subjects showed no differences, as a group, between 60 and 83 dBA conditions. Also, the moderate loss subjects demonstrated poorer discrimination capabilities than the other two groups at the low ambient noise level, while there were no differences among groups at the high ambient level. Recall, however, that the addition of a high attenuation HPD may degrade the discrimination abilities of persons with moderate or higher hearing loss more so than those without loss.

Noise Spectral Type Conclusions

Noise type main effect. The near-linear effect of noise spectral type on word discrimination performance evidences the dependency of speech masking on noise spectral content (Table 13). The low frequency noise resulted in the lowest discrimination scores of the three noise types (75% correct across all conditions). The approximation of white noise was second in masking effect at 82% correct on average. Finally, the high frequency noise, having primary sound pressure content at frequencies above the male voice spectrum, provided the least interference with speech discrimination (87% correct on average). This main effect of spectral noise type yielded statistically-significant differences among all spectral type pairs, though it should be strictly interpreted in light of its interaction with noise level and speaker voice level, discussed next.

Interaction with ambient noise level and speaker voice level. The trend of the main effect of spectral type was generally borne out in its interaction with noise level and with speaker voice level nested within noise level (see Tables 6 and 10). In these interactions, the same ordering of low, white approximation, and high frequency effects (and significant differences between each) occurred at 83 dBA. At 60 dBA, however, there was no difference between high frequency and white noise, though low frequency again was the most effective masker. It is evident that the power spectrum of the low frequency noise was quite intrusive on speech communication performance, regardless of the noise level at which it was reproduced. This may be explained by the fact that the spectrum of the low frequency noise (see Figure 3) exhibited more sound intensity in the realm of the male speech spectrum shown in Figure 6. Furthermore, the low frequency noise peaked at approximately 80 Hz, providing the sound pressure level necessary for upward masking into the male speech bandwidth. The high frequency noise spectrum peaked at approximately 4000 Hz, with considerable pressure content in the realm of 2000-8000 Hz, which is well into the upper range of the male speech bandwidth.

As shown in Table 6, there was no change in the ordering of noise types, with respect to their effect on word discrimination performance, when the ambient noise level was changed from 60 to 83 dBA. Howell et al. (1975), using similar, but less prominently skewed, high and low frequency masking noises, reported no significant differences between the two noises' effects on speech intelligibility. However, as S/N ratio increased, the lower frequency noise provided less masking, while as S/N ratio decreased the high frequency noise provided less masking effect. These differences were not significant, however. It appears then that the influence of various noise spectra on speech reception and discrimination is quite sensitive to the portion of the speech bandwidth that is effectively masked by the noise. Large differences in noise power spectra used in the study described herein produced statistically-different discrimination effects, while the more subtle noise differences of Howell et al., (1975), and others as well, have not demonstrated such differences.

As noted by Kryter (1985), if one knows the spectral characteristics of the noise, the speech, and the influence of upward and remote masking, it is possible to predict the effect of noise on speech intelligibility. This has been particularly well-documented for narrow-band noises (e.g., Miller, Heise, and Lichten, 1951); however, for broadband noises, such as those in this study, the prediction may be more difficult. Furthermore, the prediction of the broadband noise effects is of practical importance due to their prevalence in industrial situations where hearing protection is important and, in some cases, speech communication is necessary.

Noise spectral type and hearing configuration. The lack of a significant noise type-by-hearing configuration interaction effect, $F(6, 108) = 1.71$, $p = 0.1260$, would suggest that there were no differences among the effects of the various HPDs and unoccluded conditions as a function of the ambient noise spectra. This may seem to indicate that the selection of an HPD from this group, given any of these noise spectra conditions, is not so critical if speech discrimination is the measure of interest. (Of course, the primary concern would be that the HPD adequately attenuated the noise spectrum so that the wearer was protected.) However, the selection from a speech discrimination standpoint may be important under different conditions and it therefore warrants further research attention with different HPDs and noise spectra. A hint is provided by the data reported herein that the interaction of subject hearing configuration (SHC) and noise spectral type (NT) may be mediated by the overall noise level (NL) of the spectrum, as suggested by the significant NT-by-NL interaction discussed previously, and by the SHC-by-NL-by-NT interaction, $F(6, 108) = 2.19$; $p = 0.05$, which likely would have been statistically significant with the addition of a few more subjects.

In any case, it does appear that with typical broadband noise spectra such as those commonly found in industry and investigated in this study, an effectively protective and properly worn HPD can be expected to increase speech discrimination performance above that achieved by an unoccluded, or poorly occluded, listener in high ambient noise levels. This effect appears to be particularly reliable for those without considerable aural loss. The occlusion improvement may occur at, or perhaps even below, the 83 dBA level investigated in the present study.

RECAPITULATION

The research described herein offers several important findings that have bearing on the problem of verbal communication in noisy industrial settings, and how the use of hearing protection devices affects that communication. A brief review of the major conclusions follows. For specific detail on each effect, the reader is advised to carefully consider the statistical tables and data graphs in the "results" section.

1). Large increases in ambient noise level without maintaining a constant signal-to-noise ratio can be expected to significantly degrade speech discrimination, as has been well-docueented elsewhere.

2). Speech discrimination ability largely depends on the spectral characteristics of the ambient noise in interaction with the overall sound pressure level of the noise. For the broadband noises investigated, the low-frequency spectrum (foundry furnace) was a more effective mask (lower discrimination scores) than either the white noise approximation or high-frequency spectrum (contour saw). This was revealed at 60 dBA and 83 dBA. Furthermore, the white noise approximation was a more effective masker than high frequency noise, but at only the high noise intensity level. Spectral differences may be accounted for in upward masking effects and in spectral overlap of the critical speech bandwidth.

3). The use of HPDs in low ambient noise levels (60 dBA) may degrade speech discrimination over that achieved in an unoccluded condition. However, the effect is dependent on the spectrum of attenuation afforded by the HPD. For instance, an HPD which is weak in attenuation for low and speech bandwidth frequencies may not appreciably degrade speech intelligibility over unoccluded conditions. Therefore, this HPD may be appropriate for workers in ambient noise levels that do not require optimum protection. However, the same HPD may not provide adequate protection in high noise levels and may offer no enhancement of speech intelligibility either. On the other hand, "overprotection" in low noise levels is undesirable as well, because the highly-attenuating HPD may significantly degrade speech intelligibility.

4). HPDs, when used in high ambient noise levels (the 83 dBA level is considered to be at the low end of typical high industrial noise levels), do not degrade speech discrimination over unoccluded conditions. This was verified for a variety of HPDs: earcaps, earmuff, and earplug. Furthermore, it is quite possible to find a highly protective HPD which will afford enhanced speech intelligibility in high noise levels, as evidenced by the earplug results in this study. Again, the spectrum of attenuation of the HPD appears to be critical in this regard.

5). As evidenced in the pilot study, when wearing HPDs in noise, speakers (talkers) have a tendency to speak more quietly. The speech S/N ratio was found to be inversely dependent on the ambient noise level, with the amount of reduction in occluded voice level ranging from 2 dBA to 8 dBA. Termed the Lombard occlusion effect, and verified under different noise conditions in other studies, this phenomena will result in reduced S/N ratio if the speaker (as well as the listener) is wearing hearing protection as is usually the case in industry.

6). Listeners having a moderate (and above moderate) level of hearing loss may experience more degradation in speech communication when wearing certain HPDs than those with no appreciable hearing loss. Though there were no significant differences among unoccluded hearing level blocks in this study, when occluded by the highest-attenuating HPD, the moderate hearing loss subjects did more poorly than either of the other (better hearing) subject groups. However, inadequate protection at high noise levels would further contribute to hearing loss and therefore, to reduced speech intellibility.

7). It appears that properly-selected HPDs can be expected to maintain, or perhaps enhance in some cases, speech communication in a variety of high level industrial noises which differ in their spectral characteristics. Selection of a specific HPD to provide adequate protection and to facilitate speech communication should include examination of the noise spectrum, the HPD attenuation spectrum, and the typical voice spectrum.

SUGGESTIONS FOR FUTURE RESEARCH

In the interest of stimulating further research, several ideas which were generated from this study are proposed.

The issue of NIHL and speech discrimination while using HPD's warrants further investigation. One approach could make use of the same independent variables as did the present investigation with the exception that the subject pool be comprised of experienced NIHL industrial workers. Use of these appropriate subjects would provide a more meaningful study, specifically targeted at the industrial worker population.

Another endeavor could be aimed at the evaluation of HPD attenuation spectrum on speech discrimination. This study could again utilize the original independent variables, however, only HPD's with large, equal NRR's should be included. In this way, any differences in speech discrimination could be attributed specifically to the attenuation spectrum of the HPD.

A final suggested study could evaluate realistic speech S/N ratios (occluded vs. unoccluded) used by industrial workers in varied noise intensity levels and spectral types. The purpose of this study would be to establish a foundation for appropriate S/N ratios to be used in future HPD/Communication studies. Independent variables should include: noise level and spectral type, HPD type, realistic speaker-listener distances, and speaker's degree of hearing loss.

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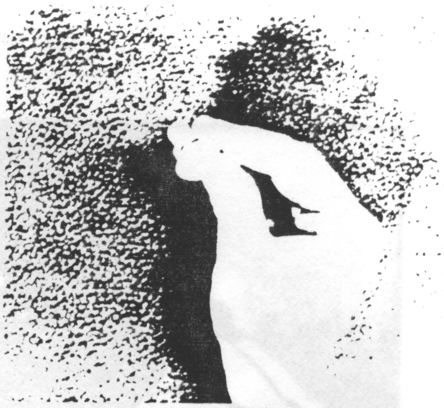
APPENDIX A

DETAILED INSTRUCTIONS FOR

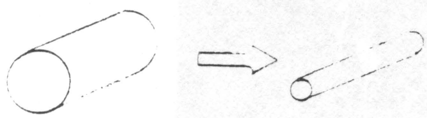
HPD INSERTION/DONNING

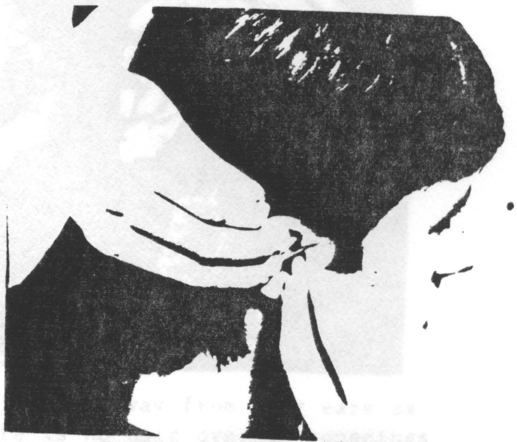
(One Example Each for Earplug, Earcap, and Earmuff)

(EAR)



STEP 1. Roll, rather than squeeze, one earplug into as small a diameter as possible, using the thumb and first two fingers.





STEP 2. With the opposite hand, reach over your head and pull the ear UP and BACK in order to straighten the ear canal. Quickly insert the compressed earplug well into the ear canal.

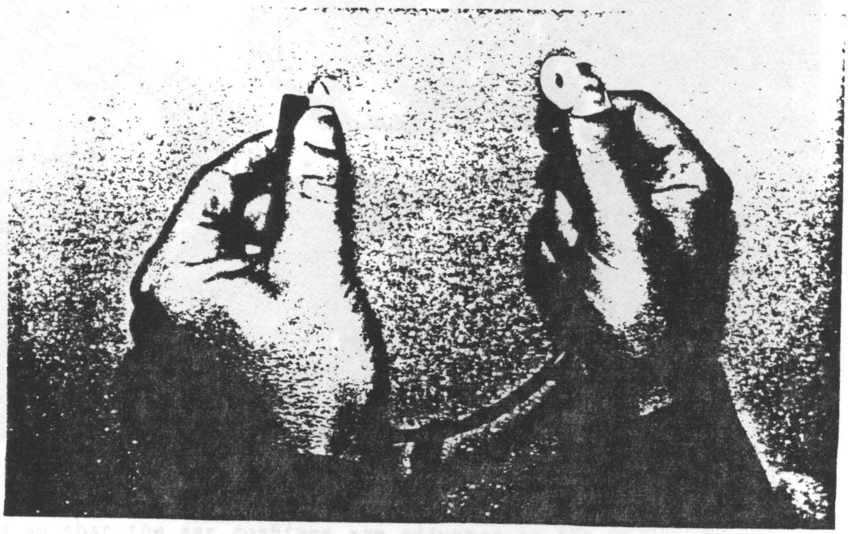
STEP 3. Once inserted, hold the earplug gently in place with the fingertip for one minute. This allows the earplug to expand and conform to the shape of the ear canal.

* Take a moment to see how the earplug feels. If you do not feel that you have achieved a "good earplug seal", please re-insert the earplug by returning to STEP 1.

Repeat STEPS 1, 2, and 3 for the other ear.

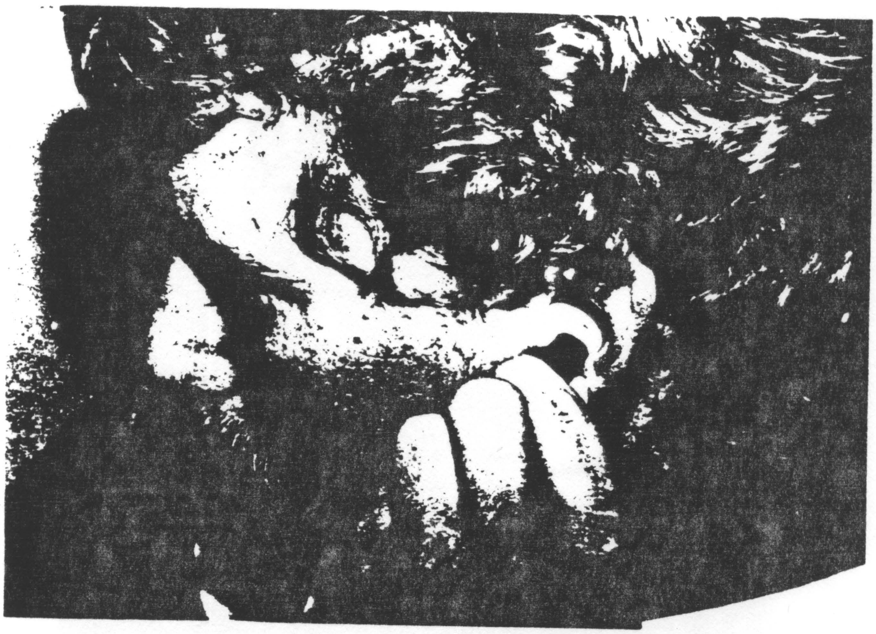
FLENTS HEADBAND 055

STEP 1. Arrange your hair so that it is behind and away from your ears as much as possible. Be sure that there is no hair over the openings of your ears.



STEP 2. Make sure that the black endcaps on the orange headband are pointed so that the white ear cushions face each other. If not, swivel the black endcaps until the cushions face

STEP 3. With the ear cushions at the top and the headband below, grasp the band on each side just below the black endcaps using the thumb and forefinger. Spread the band by pulling it apart slightly. With the headband <u>located under your chin</u>, place one cushion over the opening of each ear.



STEP 4. Now that you have the protector on, you should adjust it for maximum comfort and a snug fit. First, swivel the black endcaps forward or backward so that the ear cushions are adjusted to the angle of your ear canal. Next, gently push on the two black endcaps until the ear cushions seal in place. You may need to adjust the ear cushions (by swiveling and/or pushing them gently) several times until you have achieved a good noise-blocking seal in each ear.

STEP 5. Put you hands in your lap and take a moment to see how the protector feels. If you do not feel that you have achieved a good noise-blocking seal, or the protector is uncomfortable, re-apply the protector by returning to STEP 1. However, realize that the ear cushions should feel snug in your ears (but not painfully tight) to obtain a good noise-blocking seal.

WILLSON MUFF 365A

STEP 1. Grasp either blue earcup in one hand and the black plastic headband in the other hand. Slide the stud attaching the cup to the headband until the stud is centered in the slot in the headband. Repeat this procedure for the remaining earcup.

STEP 2. Rotate each earcup so that it is in-line (longways) with the headband.

STEP 3. Arrange your hair so that it is away from your ears as much as possible. By holding one earcup in each hand, pull the earcup slightly apart and place one earcup over each ear with the headband located over the top of your head.

STEP 4. To the extent possible, pull your hair out from underneath the ear-muff cushions so that it will not interfere with the "seal" between the cushions and your head.

STEP 5. Now that you have the earmuff on, you should adjust it for maximum comfort and for a snug fit. First, rotate the headband to the desired position over the head. Then, make sure that the earmuff cushions are against (touching) your head completely around your ears. If not, adjust the earcup positions by sliding the studs up (or down) the headband. The cushions should be slightly compressed against your head, exerting equal pressure around the ears. Now you should again pull your hair back and out from underneath the earcup cushions as much as possible.

STEP 6. Put your hands in your lap and take a moment to see how the muff feels. If you do not feel that you have achieved a good noise-blocking seal, or the muff is uncomfortable, re-apply the muff by returning to STEP 1. However, realize that the muff should feel snug on your head (but not painfully tight) to obtain a good noise-blocking seal.

APPENDIX B

SPEECH VOICE LEVEL PILOT STUDY

Prior to the main study, a pilot experiment was necessary to determine speech signal intensity levels for each speaker hearing configuration (earmuff/occluded and unoccluded) under each ambient noise level (60 and 83 dBA). The pilot study experimental design employed a four-factor, mixed-measures block design for data collection and analysis. The independent variables which were extracted from the main study included: noise type (within-subject), ambient noise level (within-subject), speaker hearing configuration (within-subject -- earmuff/occluded and unoccluded), and finally, gender (between-subjects). The dependent measure was subject speech intensity level under each treatment condition.

Four males and four females, ages ranging from 22 to 30 years (means and standard deviations 23.25, 1.26, and 25.25, 3.95, respectively) participated as subjects in the pilot experiment. All subjects were paid volunteers from among the Virginia Tech community.

The requirements for participation in the pilot study were the same as those used for the main study. The one exception was that all pilot study subjects had hearing thresholds which did not exceed 15 decibels at any one of seven frequencies tested (125, 250, 500, 1000, 2000, 4000, and 8000 Hz) for either ear. Also, all aspects of the test facility used in the pilot study were identical to those used in the main study.

During each experimental session, each of eight subjects delivered a verbal presentation of the speech material used in the main study. The presentation was delivered under each of the experimental conditions while the subject was unoccluded and earmuff-occluded (Willson 365-A) in random order. Subjects were instructed to read aloud the speech material at a voice level which they perceived to be loud enough to produce effective communication. Each treatment condition was conducted twice for each subject in a random ordering. During each presentation, the subject's voice level in the presence of the ambient noise was measured using the Larson-Davis acoustic analyzer over a 30-second integrated duration with the meter set at the slow setting. The measurements (for each subject) recorded for each treatment condition were then averaged. Next, the speaker's voice level was mathematically isolated from the measured combination of speech level and ambient noise level. The average voice level was then collapsed across the three noise types and two genders to yield an occluded and unoccluded voice level value for each ambient noise level of 60 and 83 dBA. In this manner, realistic noise levels were obtained for the two ambient noise levels for both occluded and unoccluded conditions.

The mean dBA values obtained for the uttered speech in the four conditions were as follows:

		Speaker Configuration	
		Occluded	Unoccluded
Ambient Noise Level	60 dBA	72	74
	83 dBA	79	85

The final values used in the reception/discrimination study were derived from these values after holding S/N ratio constant for the unoccluded condition to achieve some degree of experimental consistency. In the unoccluded condition, S/N ratio was set to +5, resulting in a speech level of 65 in the 60 dBA ambient and 88 in the 83 dBA ambient. Then the interaction of the occlusion and noise compensation effects were considered to set the occluded condition voice level. For 60 dBA ambient, the pilot occluded-unoccluded difference was 74-72=2; therefore, the unoccluded level of 65 was reduced to 65-2=63 for the occluded presentation. Likewise, for 83 dBA ambient, the pilot occluded-unoccluded difference was 85-79=6; therefore, the unoccluded level of 88 (for a +5 S/N ratio) was reduced to 88-6=82 dBA for the occluded presentation. This resulted in final dBA values for the speech level presentation as follows:

		Speaker Configuration	
		Occluded	Unoccluded
Ambient Noise Level	60 dBA	63	65
	83 dBA	82	88

These values were used to set the voice level in the presence of a given noise level for the experimental treatments.

APPENDIX C

THE SIXTEEN EXPERIMENTAL COMBINATIONS

	1-o	1-u	2-o	2-u
Subject	earplugs	earplugs	earplugs	earplugs
Noise	60 dBA	60 dBA	83 dBA	83 dBA
Speaker	occluded	unoccluded	occluded	unoccluded
	3-o	3-u	4-o	4-u
Subject	earcaps	earcaps	earcaps	earcaps
Noise	60 dBA	60 dBA	83 dBA	83 dBA
Speaker	occluded	unoccluded	occluded	unoccluded
	5-o	5-u	6-o	6-u
Subject	earmuffs	earmuffs	earmuffs	earmuffs
Noise	60 dBA	60 dBA	83 dBA	83 dBA
Speaker	occluded	unoccluded	occluded	unoccluded
	7-o	7-u	8-o	8-u
Subject	unoccluded	unoccluded	unoccluded	unoccluded
Noise	60 dBA	60 dBA	83 dBA	83 dBA
Speaker	occluded	unoccluded	occluded	unoccluded

APPENDIX D

PRE-EXPERIMENTAL QUESTIONNAIRE

Pre-Experimental Questionnaire

Name: ____________________________________

Phone: ____________________

Age: _____

Sex: _________

1. Is your native speaking and writing language; English?

   _________ Yes _______ No

2. Have you ever used hearing-protection devices either at work, home, or elsewhere?

   ________ Yes ________ No

3. If "yes" in question 2, what was your reason for wearing the hearing protection device?

   ____

   ____

   ____

4. Have you ever participated in an experiment which included hearing testing? This does not include audiometric testing by medical personnel.

   ________ Yes ________ No

5. Have you ever participated in an experiment which included the audible detection of words?

________ Yes ________ No

6. Do you have any of the following hearing problems?

________ Tinnitus (Ringing in the ears)

________ Allergies which affect your hearing

________ Excessive ear wax

________ Other (Please specify) ______________________________

____

____

7. Have you ever had excessive ear wax removed by a physician?

________ Yes ________ No

If yes, how recent was the last treatment? ____________________

8. How did you find out about this experiment?

____

____

____

APPENDIX E

PARTICIPANT'S CONSENT FORM

Participant's Informed Consent

This experiment is an investigation of human speech communication abilities in different noise environments. The experiment will be conducted over two sessions. In the first session, you will be given a hearing test and asked to fill out a brief questionnaire regarding your experience with noise and hearing protection devices. (For example, have you worn earplugs or earmuffs before?) During the second session, you will be asked to listen to and record (on a response sheet) recorded words which will be presented to you via loudspeakers.

During the word presentations, you will hear three different types of noise (or a quiet condition) while either wearing a hearing protection device or not. The three noises will be presented at a level of 60 dBA (decibels) and 83 dBA for a short period of time (approximately 3 minutes each). The noises will be typical sounds actually recorded from industrial or office settings.

No part of this experiment should cause you any permanent harm. However you may find some of the noise conditions to be loud or annoying. The individual noise exposures will not exceed 85 dBA over a 15-minute period. These levels of exposure are well below the Occupational Safety and Health Administration allowed levels for industry which are 85 dBA over an 8-hour period. However, if at any time you feel uncomfortable with the noise exposure, you may inform the experimenter and discontinue participation if you feel it necessary. You will then be paid only for the portion of time that you have completed. Of course, the experimenter and graduate students involved would like for you to complete the study so that your data will be usable.

During portions of the experiment, you will be asked to wear earmuffs, earplugs, and ear canal caps (similar to a small earmuff). These are typical hearing protection devices used in many U.S. industries by thousands of workers. The experimenter will help you fit the devices. If they feel uncomfortable or become uncomfortable during the experiment, inform the experimenter and he will adjust their placement. Do not adjust them yourself. Earmuffs and earcaps are fully sanitized after each subject and you will be allowed to keep the new set of earplugs that you will wear in the study. They are reusable.

The duration of the combined sessions will be approximately four and one-half hours. You will be paid $4.00 per hour for your participation.

After you have completed the two sessions, please do not discuss the experiment with other individuals until after November 31, 1986. Persons with prior knowledge of the experiment who serve as subjects will bias the experimental results and ruin the validity of the study.

As a participant in this experiment, you have certain rights as stated below. The purpose of this sheet is to describe these rights to you and to obtain your written consent to participate.

1. You have the right to discontinue participating in the study at any time for any reason. If you decide to terminate the experiment, inform a member of the research team and he will pay you only for the portion of time you have spent, at a rate of $4.00 per hour.

2. You have the right to inspect your data and to withdraw it from the experiment if you feel that you should. In general, data are processed and analyzed after all subjects have completed the experiment. Subsequently, all the data are treated <u>anonymously</u> and <u>confidentially</u>. Therefore, if you wish to withdraw your data, you must do so immediately after your participation is completed, otherwise your name cannot be associated with your data.

3. You have the right to be informed as to the general results of the experiment. If you wish to receive a summary of the results, include your address (three months hence) with your signature on the last page of this form. If after receiving the summary, you would then like further information, please then contact the Auditory Systems Laboratory and a full report will be made available to you. To avoid biasing other potential subjects, you are requested not to discuss the study with anyone until after November 31, 1986.

4. The faculty and graduate student of the research team sincerely appreciate your participation. They hope that you will find the experiment an interesting experience. If you have any questions about the experiment itself or about your rights as a participant, please do not hesitate to ask at this time. The investigators will try to answer them, subject only to the constraint that the results will not be pre-biased by a detailed answer.

Participant's Consent Form

Auditory Systems Laboratory

Department of IEOR

Room 538 Whittemore Hall

Virginia Tech

Blacksburg, VA 24061

(703) 961-7962

Your signature below indicates that you have read and understood the nature of the study and your rights as a subject and that you wish to participate in the experiment. Thank you for your interest in our research.

Name (Printed): ____

Address: ____

____

Phone: ______________________

Signature: ____

(Please keep for future reference.)

The research team consists of Mr. Matt Horylev, graduate student in IEOR and Dr. John G. Casali, Director of the Auditory Systems Laboratory. They can be reached at the following address and phone number below:

Auditory Systems Laboratory
Department of IEOR, Room 538 Whittemore Hall
Virginia Tech, Blacksburg, VA 24061

(703) 961-7962

Also, if necessary, questions about your rights as a participant may be directed to the chairman of the University Review Board, address and phone number below:

Mr. Charles Waring
301 Burruss Hall
Virginia Tech, Blacksburg, VA 24061

(703) 961-5283

APPENDIX F

ORIGINAL ISOPHONEMIC WORD LISTS

Original Word Lists

(1)	(2)	(3)	(4)	(5)
ship	fish	thud	fun	fib
rug	duck	witch	will	thatch
fan	gap	wrap	vat	sum
cheek	cheese	jail	shape	heel
haze	rail	keys	wreath	wide
dice	hive	vice	hide	rake
both	bone	get	guess	goes
well	wedge	shown	comb	shop
jot	moss	hoof	choose	vet
move	tooth	bomb	job	June

(6)	(7)	(8)	(9)	(10)
fill	badge	bath	hush	jug
catch	hutch	hum	gas	match
thumb	kill	dip	thin	whip
heap	thighs	five	fake	faith
wise	wave	ways	chime	sign
rave	reap	reach	weave	bees
goat	foam	joke	jet	hell
shone	goose	noose	rob	rod
bed	not	got	dope	vote
juice	shed	shell	lose	shook

(11)	(12)	(13)	(14)	(15)
man	have	kiss	wish	hug
hip	whizz	buzz	dutch	dish
thug	buff	hash	jam	ban
ride	mice	thieve	heath	rage
siege	teeth	gate	laze	chief
veil	gauge	wife	bike	pies
chose	poach	pole	rove	wet
shoot	rule	wretch	pet	cove
web	den	dodge	fog	loose
cough	cosh	moon	soon	moth

APPENDIX G

MATRIX FOR WORD LIST COMBINATIONS

Experimental Word List (30 words each)	Original Word Lists (10 words each)		
(1)	1	2	3
(2)	4	5	6
(3)	14	8	9
(4)	10	11	12
(5)	13	14	15
(6)	1	4	7
(7)	2	5	8
(8)	3	6	9
(9)	7	10	13
(10)	8	11	14
(11)	9	12	15
(12)	1	5	9
(13)	2	6	7
(14)	3	4	10
(15)	7	11	15
(16)	8	12	13
(Pract.)	3	10	14

APPENDIX H

SUBJECT RESPONSE SHEET

RESPONSE SHEET

SUBJECT # _____

Please print your responses.

1. ____________	11. ____________	21. ____________
2. ____________	12. ____________	22. ____________
3. ____________	13. ____________	23. ____________
4. ____________	14. ____________	24. ____________
5. ____________	15. ____________	25. ____________
6. ____________	16. ____________	26. ____________
7. ____________	17. ____________	27. ____________
8. ____________	18. ____________	28. ____________
9. ____________	19. ____________	29. ____________
10. ____________	20. ____________	30. ____________

APPENDIX I

SUBJECT INSTRUCTIONS

Subject Instructions

During each testing session, you will be seated back-to-back with another subject in the soundproof chamber. Several word-lists, each comprised of 30 recorded words, will be presented to you by way of two loudspeakers located directly in front and behind you. The words are single syllable, commonly-used words (ie, cat, fan, book). During the test you <u>must</u> keep your head facing the loudspeaker in front of you. Do not look at or talk to the other subject.

Each presentation of a word list will be accomplished under a unique set of experimental conditions (e.g., while you are wearing a hearing protection device and in a low noise level background). (When a noise sound is presented to you it will also originate from the loudspeakers in front and behind you.)

Your task during the test is to record (print) each word presented to you on a response sheet which you will be provided with. Once the test begins, <u>keep your eyes on your own response sheet and do not communicate with your fellow subject</u>.

The presentation of each word will occur only once, therefore, if you have difficulty in detection or reception of a word, please answer to the best of your ability. It is extremely important that you provide a <u>complete</u> written response for each word presentation, therefore, respond to <u>all</u> words presented to you and please print a <u>complete</u> word when responding.

For each test session, you will wear one of three types of hearing protection devices (earplugs, earcaps, or earmuffs) or have uncovered ears. When a hearing protection device is given to you, the experimenter will assist you in putting the device on. It is important that the hearing protection device is fitted tightly and that it is not readjusted at any time during the test. Therefore, do not adjust the hearing protection device at any time after it has been fitted to you by the experimenter. If it is uncomfortable after the experimenter fits it to you, please let him know immediately. Also, wait for the experimenter's signal at the completion of each test to remove the hearing protection device.

Once you have a hearing protection device on (if necessary) are seated, and are given a response sheet, the experimenter will leave the chamber and the test will begin. The experimenter will announce (via intercom) when a test is about to begin and also when the test is completed.

A two-way intercom system is installed in the sound chamber which allows communication between yourself and the experimenter at any time during a test session. However, once a word list presentation begins, focus your attention on listening and responding to the words and also maintain a quiet disposition so that you will not disturb the listening task.

You will need to listen and respond to a total of 16 word lists, with each word list presentation lasting approximately 5 minutes. At the conclusion of the tests you will be paid for your participation.

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