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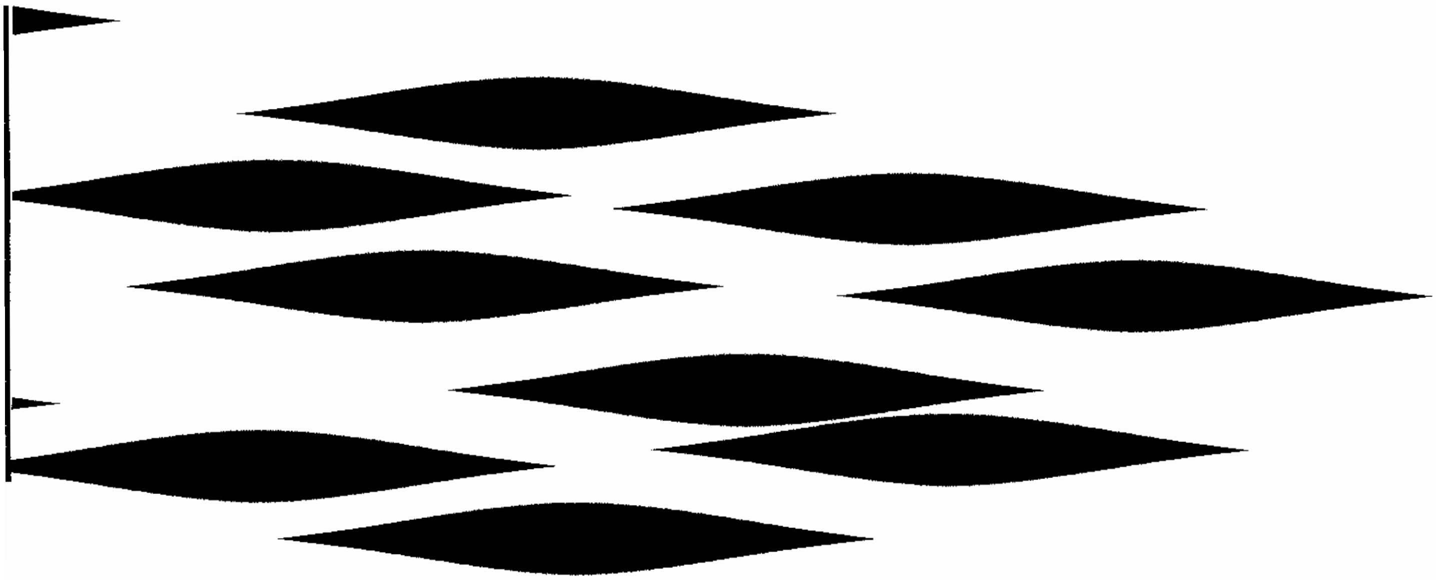
COMMUNICATION AND JOB PERFORMANCE IN NOISE: A REVIEW



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COMMUNICATION AND JOB PERFORMANCE IN NOISE: A REVIEW

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Preface

The idea for this monograph originated in conversations between the author and personnel from the U.S. Army Human Engineering Laboratory at Aberdeen Proving Ground. The substance of the conversations was as follows: Soldiers and other Army personnel perform their duties in tanks, helicopters, and other environments where the noise levels are often very high. We know that the noise must make communication difficult or even impossible, but how is the personnel's performance impaired and what are the consequences of these communication problems?

In fact, very little is known about the consequences of communication failures or other performance decrements, either in the military or in industry. There is anecdotal evidence in industry and in construction of people who were involved in accidents because they failed to hear warning shouts or signals. In addition, troops jumping out of helicopters are reported to have temporary hearing threshold shifts so severe that they are not able to detect enemy movements. Sometimes efforts at preventing noise-induced hearing loss are blamed for causing safety hazards. For example, miners and other workers often refuse to wear hearing protectors because they believe that these devices will prevent them from hearing necessary speech and warning signals. Mechanics working around jet engines have reported dizziness and nausea from the high noise levels, which could result in a safety hazard. But systematic investigations into the role of noise in accidents and communication failures are virtually nonexistent.

The best approach appeared to be to examine thoroughly the existing research in all aspects of the issues that lead to communication failures and performance decrements. At what levels does noise become a hindrance to communication? To what kinds of communication? How do we measure these effects? What is the status of modern-day communication systems? What is the role of hearing loss (usually noise-induced)? How about hearing protectors: Do they help or hinder communication, and in what circumstances? Does noise really disrupt job performance (even when communication is unnecessary)? If so, what levels and types of noise can degrade performance? And what kinds of jobs? This monograph discusses the abundance of laboratory evidence and some information from field studies that illuminate these issues.

After a preliminary look at the literature, it appeared that the general topic of noise and performance would be most efficiently examined by dividing it into four categories: (a) the effects of noise on the perception of speech and warning signals, (b) the effects of hearing loss on the perception of speech and warning signals, (c) the effects of hearing protectors on the perception of speech and warning signals, and (d) the effects of noise on task performance.

Eventually, each of these four categories became the subject of an Army technical report, issued in June 1989. The task of gathering and analyzing the literature and drafting the reports was supported by the U.S. Army Environmental Hygiene Agency, and the effort was contracted through Gallaudet University, where the author was adjunct professor of audiology. Because the four reports represented different aspects of one broad subject area, it seemed advantageous to pull them together into a monograph entitled "Communication and Job Performance in Noise: A Review."

The information in this monograph should be helpful to a variety of users. Those who develop and specify communication equipment and work environments in both the military and industry should benefit from the relevant research that has been performed by others. Military and industrial psychologists and managers who are concerned with maximizing efficiency and productivity could benefit especially from the information in Chapter 4 (Noise and Job Performance). Consultants in acoustics, audiology, industrial hygiene, and perceptual psychology may also find this review and analysis helpful, as might students in these areas. Finally, anyone who is planning a research program in any of these areas will now have an existing literature survey, as well as suggestions for some of the more pressing research needs in each area. There is a great deal to be said for avoiding the reinvention of the wheel.

The author would like to acknowledge the institutions and individuals whose contributions and assistance made this monograph possible. The Army Human Engineering Laboratory provided financial support, and Georges Garinther, the contract's project officer, deserves special thanks for his patient and cheerful approach to a series of delays and the usual practical problems. The contract was managed by Gallaudet University, where B. Patrick Cox, then Chairman of the Department of Audiology and Speech-Language Pathology, performed the necessary administration, and Monica Payne provided word processing that was as close to perfection as one could imagine. Thanks also go to each section's reviewers, who were selected by the Army. Although most of them remain anonymous, a few who have identified themselves include G. Richard Price, William Melnick, Karl Kryter, and Karl Pearsons.

Special thanks are owed to Lawrence Feth, editor of *ASHA Monographs,* and Henning von Gierke, both of whom provided helpful suggestions for improving the manuscript. Finally, my husband, Jack Hardesty, deserves at least honorable mention for his patience, advice, and good-humored support over the years during which this monograph came together.

Alice H. Suter

Chapter 1

The Effects of Noise on the Perception of Speech and Warning Signals

Not only is speech communication the most important of human social activities, but the effective communication of speech and warning signals is vital to the success of most military and industrial programs. The consequences of communication failures can range from a minor irritation to a major disaster, depending on the importance of the incorrectly perceived message. These communication failures can be costly in terms of production, mission objectives, equipment, and, in the extreme, human life. Adequate technology exists to permit effective communication in most situations, but it is not always implemented. In some conditions, a high level of intelligibility is unnecessary because the communication task is very simple. In others, however, highly intelligible communications are needed to convey complex or unexpected messages in emergency situations. It is important to assess each communication situation so that the right balance can be made between economy and effectiveness. Unnecessary sophistication in communication systems should be avoided, but too much emphasis on economy can lead to greater expense in the long run.

The purpose of the literature search and analysis that composes this section is to elucidate the present state of information on the effects of noise on the perception and recognition of speech and warning signals and to describe some of the circumstances in which communication improvements or degradations may occur.

To gain an understanding of speech and warning signal communication in various occupational environments, it is first necessary to explore some theoretical and practical aspects of communication, especially as it is affected by noise. This section will cover speech variables, namely, speech level; materials used for testing communication systems; and degradations by filtering and masking. It will include a discussion of the transmission of speech from talker to listener; various talker and listener variables, such as the effect of non-native languages on both; and some of the more prominent methods for predicting the effects of noise and other degrading factors on speech intelligibility. The section will conclude with discussions of criteria for acceptable communication and for warning signal detection, and a summary of the effects of noise on speech and warning signals.

1.1 SPEECH VARIABLES

The intelligibility of speech depends on a large number of variables. The framers of ANSI S3.14 (ASA, 1977) divide them into acoustic, nonacoustic, and random or quasirandom factors. Acoustic factors include the level and spectrum of the speech signal at the listener's ear; the level, spectral, and temporal characteristics of the interfering noise; differences in the spatial locations of the speech and noise sources; and reverberation effects. Nonacoustic factors include the talker's speech habits, the size of the message set, the probability of occurrence of each unit, the listener's motivation and familiarity with the speech material, and visual cues. Random or quasirandom factors, which set an "upper bound" on the precision with which intelligibility can be estimated, include individual differences between talkers and listeners, day-to-day variations in their effectiveness, effects of randomization in the choice of test material, random sampling errors, and the listener's age and hearing sensitivity (ASA, 1977).

1.1.1 Speech Level

Any predictions of speech intelligibility are likely to be influenced by the procedure used to measure speech level. One of the difficulties is the wide dynamic range of speech, which is as much as 30 dB between the most and least intense phonemes (Hood & Poole, 1977; Pearsons, 1983; Webster, 1984). Another is a satisfactory method of accounting for the pauses between utterances. Various measurement methods have been proposed. One of the most popular methods is the long-term rms level monitored with a sound level meter or a VU meter. However, this method involves a certain amount of subjective judgment, and, according to Pearsons (1983), the speech sample should be at least 10 sec long. Kryter (1984) maintains that the average A-weighted peak level of each word measured with a sound level meter set on slow response is approximately equal to the unweighted L_{eq}. Pearsons (1983) believes that the integrating sound level meter or computer shows promise (see also Suter, 1978), but points out that there are no standard techniques available.

Standardization is currently being considered by Working Group S3-59 for ANSI S3.38, "Measurement of Speech Levels" (ASA, 1986). A preliminary draft of this standard favors a method called the Equivalent Peak Level (EPL) developed by Brady (1968), with long-term rms measured in real time as an alternative. The EPL method consists of measuring the rms level above an arbitrary threshold and calculating the peak of a log-uniformly distributed speech sample that would have the same rms level. The advantages of EPL are that it (a) is expressed by a single number, (b) is uninfluenced by silent intervals, (c) is independent of the threshold setting of the speech detector, and (d) follows known level changes on a dB-for-dB basis (Brady, 1968).

Although the various methods identify different speech levels, the relationships between these levels are fairly uniform. Most investigations show the unweighted rms level to be about 4 dB above A-weighted rms level, and the EPL to be 8–10 dB above unweighted rms (Pearsons, 1983; Steeneken & Houtgast, 1978). According to Kryter (1962a), speech peaks, defined as the level exceeded by only 1% of the speech signal, are equal to the rms level +12 dB. The long-term rms level may be estimated by taking the average speech peaks in quiet, measured with a sound level meter set on C-weighting and slow response, and subtracting 3 dB (Kryter, 1962a).

Speech level will change according to the vocal effort expended. Pickett (1956) found the range of vocal force varied from 36 dB, the level of a forced whisper, to 90 dB for a heavy shout. Figure 1 shows speech level as a function of vocal effort according to Pearsons, Bennett, and Fidell (1977) and including data from Beranek (1954). The entire range extends from about 48 dB to 92 dB.

People will increase their vocal effort automatically with increasing distance between talker and listener and with elevation in background noise level. Gardner (1966) found that people raise their voices approximately 2 dB with every doubling of distance between about 1 and 4 meters. Kryter (1946) reports a 3-dB increase and Webster and Klumpp (1962) report a 5-dB increase for every 10-dB increase in background noise level. Webster and Klumpp (1962) identified the same increase in vocal effort as a result of a doubling in the number of talkers around a communicating pair (the "cocktail party" effect). Pearsons and his colleagues (1977) measured speech levels in face-to-face conversation at one meter, and found an increase of 6 dB for every 10-dB increase in background noise level between 48 and 70 dB, above which talker and listener moved closer together.

Changes in the speech spectrum and rate of utterance also occur as vocal effort increases. Webster and Klumpp (1962) found that speech rate decreased with increasing noise level, although it tended to increase with increasing numbers of competing talkers. Figure 2, also from Pearsons et al. (1977), displays the definite shift toward higher frequency speech energy with increasing vocal effort. People change their vocal effort according to their activity, even without increases in background noise level. They tend to talk louder when reading prepared text than they do in casual conversation. They also raise their voices when talking before an audience, on the telephone, and even in the presence of a microphone (Webster, 1984). On the basis of data from van Heusden, Plomp, and Pols (1979), Houtgast advocates distinguishing between public and private communication, with the former being 9 dB louder than the latter (Houtgast, 1980). The intelligibility of amplified speech remains good up to sound pressure levels as high as 120 dB, but as soon as noise is introduced, even with a speech-to-noise ratio as favorable as 15 dB, intelligibility begins to drop off above a sound pressure level of 90 dB (Pollack & Pickett, 1958). Overloading the auditory system is presumably responsible for this drop in intelligibility. Unamplified speech is another matter. Intelligibility falls off abruptly above a speech level of 78 dB. However, at speech levels below 55 dB, intelligibility falls off gently at first and then abruptly (Pickett, 1956).

1.1.2 Speech Materials

Spoken language contains numerous constraints that add to its redundancy and make it easier to understand. This is indeed fortunate for the person with impaired hearing and for any listener in a time of emergency. These constraints result from any language's grammatical structure, the context of the word or sentence, limitations in vocabulary size, the length of words, and the listener's familiarity with the speech material. The greater the constraints, the higher the speech intelligibility scores for the same speech-to-noise ratio. An example of this is the relative intelligibility of specialized vocabularies, such as the ones used by air traffic controllers. Frick and Sumby (1952) describe four steps of constraints in pilots' receipt of control tower messages: From an infinite set of possible messages one moves to a set

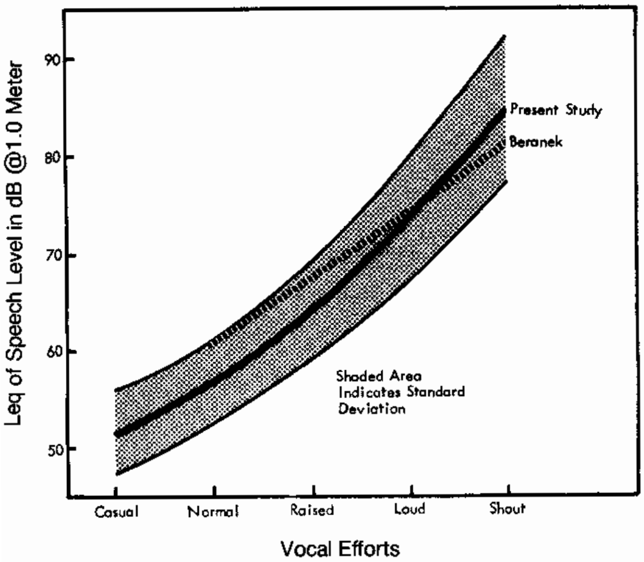

FIGURE 1. Speech levels for various vocal efforts (Pearsons et al., 1977). Reprinted by permission.

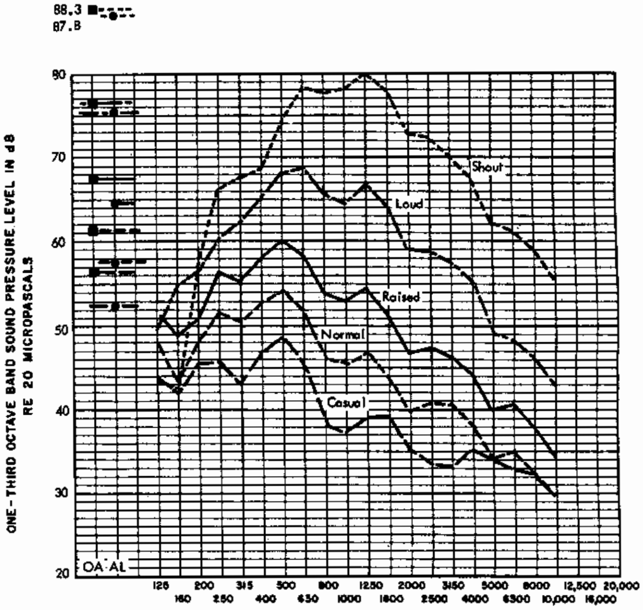

FIGURE 2. Average speech spectra for male talkers at five vocal efforts. (Pearsons et al., 1977). Reprinted by permission.

of alphabetical sequences, then to a set of English sentences, to air language with its own particular grammar, and finally to the tower messages with their own procedural constraints. The estimated redundancy with respect to what could have been conveyed is 96%. The authors note that this degree of redundancy is very inefficient in terms of information transfer, but they point out that communication systems tend to be noisy and the communication link between pilot and control tower has a low tolerance for error, so redundancy provides an important form of insurance.

Intelligibility increases directly as the number of possible words in a message set decreases. Similarly, for a given amount of intelligibility, the speech-to-noise ratio can be reduced with proportional decreases in the size of a message set. Miller, Heise, and Lichten (1951) found that a decrease in message size from 256 to 4 monosyllables corresponded to a 12-dB decrease in speech-to-noise ratio. For this reason, "closed-set" tests, such as the Modified Rhyme Test (House, Williams, Hecker, & Kryter, 1965), yield better intelligibility scores than "open set" tests of monosyllabic words or nonsense syllables, for a given speech-to-noise ratio. Other investigations have shown that long words are more intelligible than short ones (Rubenstein, Decker, & Pollack, 1959), and two-syllable words are more intelligible when the accent is on the second syllable (Black, 1952).

Figure 3 from ANSI S3.5 (1969) shows the relative intelligibility of various speech materials as a function of speech-to-noise ratio (represented by Articulation Index values). The order of difficulty is from the least intelligible, 1,000 nonsense syllables; to 1,000 phonetically balanced (PB) words; to rhyme tests, 256 PBs, and unfamiliar sentences; to familiar sentences; to the most intelligible, a vocabulary limited to 32 PB words. The authors caution the reader that these relations are approximate, as they depend on the type of material and the skill of talkers and listeners.

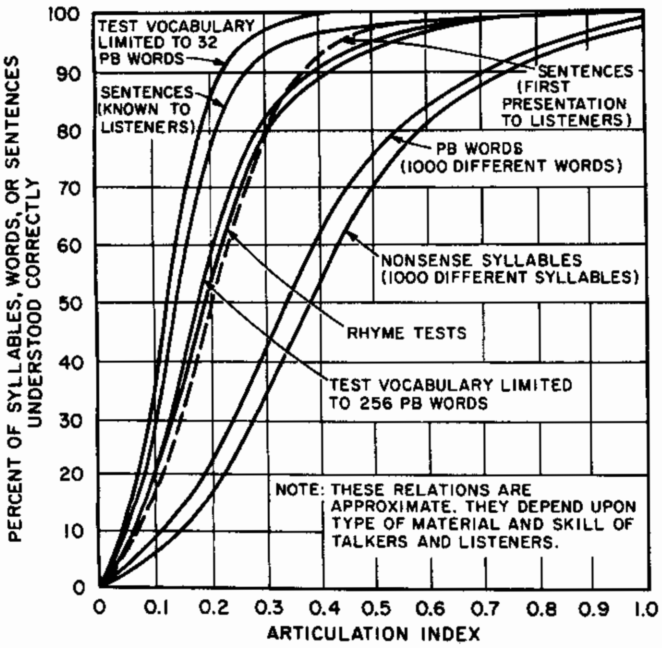

FIGURE 3. Relative intelligibility of various speech materials as a function of Articulation Index value. (ANSI, 1969. Reprinted by permission. Copies can be purchased from ANSI at 1430 Broadway, New York, NY 10018.)

Features within words can cause some words to be more intelligible (resistant to masking or filtering) than others. For example, prosodic features and vowels are more easily identified than consonants (Webster & Allen, 1972). Medial position phonemes are more intelligible than consonants in the initial and final position and final consonants are more easily identified than initial consonants under adverse conditions (Clarke, 1965).

In an effort to improve the reliability of the Harvard list of PBs, Hood and Poole (1977) noted that the intrinsic intelligibility of these words covered a range of at least 30 dB. (The authors considered this large range a necessary feature of a good intelligibility test.) By eliminating 5 "rogue lists," Hood and Poole brought the performance-intensity functions of the remaining 15 lists into close agreement. During this process, they analyzed the difficulty of all words in the 20 lists, having tested each word 36 times. The result is a table that lists the relative intelligibility of all of the Harvard PBs, from most intelligible (*jam, our, rope, wild,* and *will*) to least intelligible (*rave, fin, pun,* and *sup*). This table could be useful in assessing the difficulty of words to be used in special phraseologies or for testing the articulation of specific systems.

The helpful redundancy in speech is derived from a number of different features, as explained above. In other words, it is as if we say the same thing in a variety of ways. The question arises, then, as to whether simple repetition of the same word will increase its intelligibility. Investigations of this question have produced moderately encouraging results. Miller et al. (1951) found that three successive presentations of the same word improved intelligibility by 5 to 10%, depending on the speech-to-noise ratio. Lazarus (1983) quotes a German colleague (Platte, 1978, 1979) as finding that large variances can be avoided by triple repetition. Using the Harvard PBs, Thwing (1956) tested the effects of one through four presentations of the same word (e.g., "Item 26: dog, dog, dog") at three speech-to-noise ratios. The results showed a slight improvement between the first and second presentations, but nothing after that. The greatest improvement was at the most favorable speech-to-noise ratio. Other investigators found no improvement for repetition of numbers (Moser, 1954) or nonsense syllables (Black, 1955). Hood and Poole (1977) noticed that words duplicated (by chance) in separate lists were missed on some occasions but not on others. They cite Brandy (1966) as finding the same result, and suggest that the cause lies in slight variations in the talker's voice production, not only among different talkers but at different times with the same talker. So, at least for words, there appears to be a moderately beneficial effect of at least one repetition. In view of the increased opportunity for talker variations, it would seem reasonable that these benefits would be somewhat greater for phrases and short sentences.

As stated above, word familiarity is another important consideration in the intelligibility of a spoken message. According to Rubenstein and Pollack (1963), intelligibility is a simple power function of the probability of a word's occurrence. In an effort to develop word lists with familiarity greater than the Harvard PBs, Hirsh et al. (1952) developed the CID W-22 list of 200 familiar PBs, Peterson and Lehiste (1962) developed a CNC (Consonant Vowel Nucleus Consonant) list of 500 PBs, and Tillman and Carhart (1966) compiled the 200 words that comprise the NU Auditory Test 6, which was developed for and used extensively by the U.S. Air Force (Webster, 1972).

In a comprehensive compendium of speech testing materials, Webster (1972) discusses and reprints various speech materials and standard phraseologies used in testing communication systems. These include a selected list of Navy Brevity Code words, along with ICAO phonetic spelling words and digit pronunciation (Moser & Dreher, 1955), a transcription of radio transmissions of U.S. Naval aircraft over Vietnam (Webster & Allen, 1972), and a list of words frequently used in USAF aircraft compiled by Donald Gasaway. Gasaway's list includes statistics on word familiarity according to word-frequency counts from Thorndike and Lorge (1952) and a code showing whether they are represented in various standard word lists and among Brevity Code words. Webster's compendium also includes lists of tactical field messages from the U.S. Army Test and Evaluation Command (1971), 150 phrases from the flight deck of aircraft carriers developed by Klumpp and Webster (1960), and lists of aviation maintenance/supply support messages developed by Webster and Henry (NAVSHIPS, 1972).

One of the difficulties involved in speech testing using large sets of monosyllables, such as 1,000 Harvard PBs, is the fact that talker and listener crews must be thoroughly trained. Webster (1972) states that such training takes weeks to perform! In an effort to reduce or eliminate training time, Fairbanks and his colleagues developed the closed-set Rhyme Test (Fairbanks, 1958), which has gone through a series of modifications (House et al., 1965; Kreul et al., 1968). An interesting innovation is the Tri-Word MRT (Williams, Mosko, & Greene, 1976), where words are presented in triplets instead of individually. The principal advantage of this test is its speed: the investigators found that 51 words could be presented in only 2.3 min as opposed to 5 min for the MRT. Another variation developed by Voiers (1977) is the Diagnostic Rhyme Test (DRT), which can be used to identify the particular features of speech (in initial consonants only) that are affected by a communication system.

The American National Standard Method for Measurement of Monosyllabic Word Intelligibility (ANSI 3.2-1960) (R1982), specifies the Harvard PBs as test materials. A current draft revision (ASA, 1988) has added the MRT and DRT. According to the new standard, the three tests have been shown to be highly correlated with each other as well as with other intelligibility test materials. All three tests provide the same rank orders and magnitude of differences among systems when used with a large number of communication systems. The new draft also specifies the method outlined in ANSI S3.38 for measuring speech level (ASA, 1986). The scope of the new draft standard covers the testing of all kinds of communication systems (with the exception of speech recognition devices), including speech transmitted through air in rooms or out of doors; through telephonic systems including telephones, public address systems, and radios; or through complex environments including equipment, air, wire, fiber, radio, and water paths.

Sentence material can also be useful for testing communication systems. In addition to the original Harvard sentences (Hudgins, Hawkins, Karlin, & Stevens, 1947), the CID sentences (Silverman & Hirsh, 1955) were developed to resemble everyday speech, and these sentences were modified to achieve homogeneity of sentence length to form the RCID sentences (Harris, Haines, Kelsey, & Clack, 1961). Speaks and Jerger (1965) and Jerger, Speaks, and Trammell (1968) have developed synthetic sentences to reduce predictability of the key words. More recently, Kalikow, Stevens, and Elliott (1977) invented the SPIN test (Speech Intelligibility in Noise), which consists of two types of English sentences in speech-babble noise: one for which the key word is somewhat predictable from the context, and the other for which the key word cannot be predicted from the context. Both types of sentences are balanced for intelligibility, key-word familiarity and predictability, phonetic content, and length. Although its major application is in testing people with impaired hearing, it has other uses, such as the evaluation of speech processing devices (Kalikow et al., 1977). The test has recently been revised by Bilger (1984) to achieve greater equivalence among test forms.

The choice of speech materials depends on many factors, including the availability of listeners and training time, the type of system, and the conditions of use. Webster (1978) points out that the mid-range of a steep performance-intensity function is necessary for the best testing. Webster suggests that in very noisy conditions (AI of about 0.2), a closed-set test of rhyme words will yield about 50% intelligibility. At an AI of 0.35, an open set of 1,000 PB words would be more appropriate because rhyme tests would yield about 85%, which would be at or above the "knee" of the function.[1] At AIs as high as 0.8, even 1,000 nonsense syllables would produce intelligibility scores greater than 90%, so Webster advocates using other measures, such as reaction times, competing messages, or quality judgments (Webster, 1978).

1.1.3 Degradations

According to Harris (1965), ". . . not more than half the time in everyday life do we listen to clearly enunciated

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[1] In his discussion of matching intelligibility tests to AI levels, Webster refers to an AI of 0.35 as corresponding to rhyme-test scores of 75%. However, the graph reprinted from ANSI S3.5 (1965) as Figure 3 indicates rhyme scores of about 85% at this AI. This discrepancy may point up the caveat of the standard formulators, that these relations are approximate, and that they depend upon type of material and skill of talkers and listeners. It may also indicate the need for reexamining the interrelationships of these materials, especially in view of more recent additions to the available battery of test materials.

speech in quiet" (p. 825). Conditions that degrade speech, such as filtering and noise masking, are prevalent in all kinds of environments, from offices and computer rooms to classrooms, department stores, and helicopters.

Filtering of speech occurs when it is passed through almost any transmission system, such as a telephone or a radio communication system. High-frequency speech sounds are most readily affected, with a resulting loss of consonant intelligibility. The effects of filtering are exacerbated by other factors, particularly by background noise and hearing impairment.

Noise is the most common culprit, and its effectiveness as a masker depends on spectral, level, and temporal considerations. One of the most efficient maskers of speech is speech itself. To quote George Miller, ". . . the best place to hide a leaf is in the forest, and presumably the best place to hide a voice is among other voices" (Miller, 1947, p. 118). For this reason, a babble of many voices is often used in speech-masking experiments. Broadband noise can also be an effective masker. At low-to-moderate levels of noise and speech, high-frequency noise masks more efficiently because it masks the consonant sounds, which are generally higher in frequency and lower in speech power than vowels. Figure 4, from Richards (1973), displays the relative energy of speech sounds. Because of a phenomenon known as the "spread of masking," low-frequency sounds become more efficient maskers as their intensity increases. Above a sound pressure level of approximately 80 dB, low-frequency masking increases at a faster than normal rate (Kryter, 1962a) and becomes increasingly effective at masking mid- and high-frequency sounds. Low-frequency sounds, if intense enough, will mask the whole range of speech frequencies (Miller, 1947).

Noise becomes less efficient at masking speech when its levels vary with time. In its report on the effects of time-varying noise, the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) (1981) points out that varying noise produces less speech masking than continuous noise for a given AI. The report predicts 97% sentence intelligibility for a time-varying L_{eq} of 70 dB, and even 81% intelligibility at an L_{eq} of 80 dB. The report also suggests that a good "speech interference index should be some running estimate that combines background noise and time-varying noise episodes in which the noise level is within 10 dB of the peak level" (CHABA, 1981, p. 7).

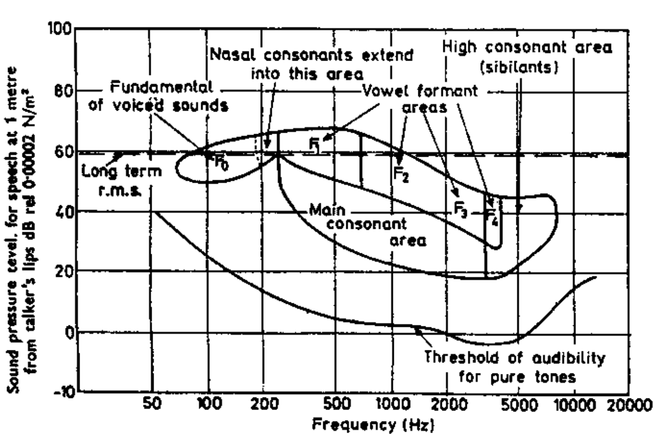

FIGURE 4. Relative energy of speech sounds. (Richards, 1973. Reprinted by permission.)

More often than not, degradations of the speech signal occur in combinations rather than singly. Talkers may be smoking, chewing, or talking rapidly (Lacroix, Harris, & Randolph, 1979). They may have their heads turned away, they may be trying to communicate at a distance, their vocal effort may be above or below the point of maximum intelligibility, or their articulation may be unclear. A very common combination of distortions is noise and low-pass filtering, which characterizes inefficient communication systems. Lacroix et al. (1979) investigated the effects of three types of distortion—increased rate of talking, interruption, and speech-shaped noise—singly, and in combination with low-pass filtering. The authors found that the reduction in speech recognition resulting from multiple distortions was considerably greater than an additive effect. According to Lacroix and his colleagues, these results corroborated similar findings of earlier investigations (Harris, 1960; Licklider & Pollack, 1948; Martin, Murphy, & Meyer, 1956).

1.2 TRANSMISSION CHARACTERISTICS

1.2.1 Distance Between Talker and Listener

Early criteria developed by Beranek (1950) gave estimated "speech interference levels" (SILs) as a function of distance and vocal effort. Based on communication in the free field, they show the expected 6-dB decrease in SIL for a given intelligibility with every doubling of distance. However, speech intelligibility will not deteriorate with distance as quickly as might be expected from the 6-dB per doubling rule because people will increase their vocal effort with increasing distance. Also, the 6-dB rule is inappropriate for indoor spaces because of room reverberation and other factors. Schultz (1984) has developed a formula for predicting sound propagation indoors, based on the frequency and sound power level of the source, room volume, and the distance from the source. Modifications to the SIL for vocal effort, reverberation, and other factors will be discussed in greater detail in a subsequent chapter.

Garinther and Hodge (1987) point out that individuals use a "communicating" voice level, meaning that they raise their voices as they feel necessary according to the distance at which they need to communicate. They cite research by Gardner (1966) to support their estimate of a 2.4-dB increase in vocal effort for each doubling of distance. An investigation of the effects of wearing a gas mask and hood showed that individuals use slightly higher voice levels in this condition, and raise their voices approximately 1.5 dB per doubling of distance (Garinther & Hodge, 1987).

1.2.2 Reverberation

Although reverberation is a necessary feature in concert halls and auditoriums, the prevailing thinking on the subject today is that its effects on speech are virtually never beneficial. Early reverberations seem to have little adverse effect if they arrive during the production of the same sound (Nabelek, 1980), but Webster (1983) and other investigators he cites (Kuttruff, 1973; Mankovsky, 1971) believe that all reflections are detrimental. In a study of the influence of noise and reverberation on speech recognition, Nabelek and Pickett (1974) found that a change in reverberation time of 0.3 sec produced a substantial decrease in speech recognition, equivalent to a 2- to 6-dB increase in noise level. The investigators used two types of noise: one consisting of 16 impulses/sec and the other a babble of 8 talkers. Nabelek has reported that a degradation of speech perception in quiet occurs at reverberation times longer than 0.8 sec, and that the amount of the degradation depends on the size of the room (and therefore the temporal distribution of reflections), the type of speech and noise, and the listener's distance from the source (Nabelek, 1980).

In an attempt to test the effects of small-room reverberation and binaural hearing on subjects with normal hearing and subjects with impaired hearing, Nabelek and Robinette (1978) found a significant decrease in speech recognition scores between a reverberation time of 0.25 to 0.5 sec, and concluded that the adverse effects of reverberation are greater in small rooms than in large rooms. A table comparing their data to those of other researchers shows that the effect of reverberation on speech recognition may vary anywhere from 0% to 34.8%, depending on reverberation time, presence or absence of noise, and monaural or binaural listening (Nabelek & Robinette, 1978). The authors also discuss an experiment using computer-simulated reverberation consisting of a direct sound followed by five reflections, decreasing at a rate of 6 dB per reflection. Unexpectedly, the results failed to show a statistically significant difference between speech recognition scores for three simulated reverberation times. In a later simulation, Nabelek (1980) did find a difference between nonreverberant and computer-simulated reverberant conditions of 9% in the scores of subjects with impaired hearing. This simulation had been developed by Allen and Berkley (1979), whose FORTRAN program may be used to simulate a wide range of small-room acoustical conditions.

1.2.3 Spatial Location

The location of the speech and noise sources may also have an effect on speech intelligibility. The most difficult condition occurs when speech and noise are coming from the same direction. Generally, as the angle of separation becomes wider, intelligibility increases for a given speech-to-noise ratio. Plomp (1976) reports that with the speech signal coming from 0° azimuth, people could tolerate a decrease of approximately 5 dB in speech-to-noise ratio for the same intelligibility when the noise was moved from 0° to 135° azimuth. This finding occurred in nonreverberant conditions. Effects were less dramatic as reverberation time increased from 0 to 2.3 sec.

1.2.4 Monaural Versus Binaural Listening

Nature has provided us with two ears for reasons in addition to redundancy. Binaural hearing enhances our sense of a sound's location, and it increases our ability to recognize speech sounds in a reverberant space. We are able to do this by discriminating small differences in signal phase and time of arrival at the two ears. This ability is considerably better for frequencies below rather than above 1500 Hz (Littler, 1965).

Different investigators report different amounts of improvement or "binaural gain," defined as the difference in speech-to-noise ratio for a given speech recognition score. The amount of improvement depends on such aspects as reverberation, the type of masker, the spatial location of the speech and noise, the listener's hearing sensitivity, and the presence or absence of amplification. MacKeith and Coles (1971) report a 3- to 6-dB improvement from binaural summation alone (at or slightly above threshold). Nabelek and Pickett (1974) found improvements of 4 to 5 dB, unaided listening in reverberant conditions, but the gain was only 3 dB when listening through amplification. The binaural advantage appears to be greater for normal hearing than for people with impaired hearing (Nabelek & Robinette, 1978), although the latter will experience a peculiar summation when the hearing threshold levels for the two ears are dissimilar according to frequency (MacKeith & Coles, 1971).

Levitt and Rabiner (1967) have developed a method for predicting the gain in intelligibility that is due to binaural listening. They estimate the maximum benefit for single words in high-level white noise is about 13 dB, while at high intelligibility levels the benefit will be only about 3 dB (from summation). The authors suggest that binaural gain might be greater with speech as a masker, since Pollack and Pickett (1958) found advantages up to 12 dB. With respect to directionality, Plomp (1976) found that there was a binaural gain of about 2.5 dB over the monaural condition when the noise was on the side of the occluded ear, and a greater gain when the masking noise was on the side of the open ear. These advantages were fairly constant, irrespective of reverberation and azimuth of the masker. However, the data of Nabelek and Robinette (1978) and Nabelek and Pickett (1974) show sizeable increases in binaural advantage with a doubling of reverberation time.

1.2.5 Telephone Listening

Telephone circuitry filters the speech signal on both the low and high ends of the spectrum, such that the spectrum rises gradually from 200 Hz to a peak of about 800 Hz, with a gradual decline to 3000 Hz and a precipitous drop thereafter (Richards, 1973). Without the advantage of high-frequency speech information or binaural hearing, noise, either in the system or in the listener's environment, can be problematical. Noise in the listener's environment further disrupts telephone listening in that it is amplified through the same mechanism that enables talkers to monitor their voice levels, "side-tone feedback" (Holmes, Frank, & Stoker, 1983).

In an effort to evaluate the influence of a noisy background on telephone listening, Holmes et al. (1983) tested the ability of normal-hearing subjects to hear speech through a standard "500" handset. Speech was presented at a sound pressure level of 86 dB (the average level of telephone speech according to the authors) in backgrounds of multitalker babble and white noise at 65, 75, and 85 dB in five telephone conditions: transmitter off, transmitter occluded by the listener's palm, contralateral ear occluded, control (normal listening mode), and transmitter off plus contralateral ear occluded. The results showed no significant differences among conditions when the noise was at the 65 dB level, but for the less favorable speech-to-noise ratios, significantly poorer speech recognition scores were obtained during the control and contralateral ear occluded positions than during the transmitter off and transmitter occluded positions. The authors conclude that telephone listening can be improved by occluding the transmitter, but no help is derived from the popular remedy of occluding the opposite ear. Holmes and her colleagues also found that amplified telephones improve speech recognition because increases in the level of side-tone feedback are nonlinear with respect to increases in signal level. They found that if the telephone's output was increased by as much as 20 dB, the side-tone feedback increased by only about 4 to 7 dB. Thus, the speech-to-noise ratio would be more favorable, and indeed they found that speech recognition scores using an amplifier showed smaller differences between the transmitter occluded and unoccluded positions, causing the authors to recommend amplifier handsets as another remedy for telephone listening in noise.

1.2.6 Communication Systems

Communication systems have been specially designed for military and industrial use where high levels of background noise are common. Certain features have been developed to enhance the communication process in noise environments. Circumaural earcups house the receiver, providing attenuation of up to 20 to 30 dB, depending on frequency and on the effectiveness with which they are worn. The process of electronic peak clipping aids intelligibility by boosting consonant energy in relation to vowels, but the benefits of this process are limited when noise accompanies the signal (Kryter, 1984). The noise-cancelling microphone is a useful innovation, as are improvements in circuitry such as the "expander/compander" circuitry described by Mayer and Lindburg (1981).

Despite recent improvements, Mayer and Lindburg (1981) contend that most communication systems in use today are based on design concepts that are over 50 years old. The 300–3000 Hz bandwidth allows insufficient intelligibility in noise, such that aviators sometimes need to take the time to use the phonetic alphabet—time that they can ill afford. Mayer and Lindburg state further that peak clipping in typical noisy conditions can produce a distortion of the signal of up to 50%, degrading speech intelligibility to the extent that all the gains from this process are lost. They cite a worst-case condition in which peak clipping can almost destroy the intelligibility of a high amplitude "panic message." In addition, they maintain that current test procedures are outmoded. The 6cc coupler is not appropriate for circumaural earcups. ASA standard 1-1975 procedures are inappropriate because real-world, high-noise environments lead to a "pumping" action on the earcup, causing the ear cushion to be lifted off the ear, with resulting acoustical leaks. Finally, Mayer and Lindburg state that the equipment used to test the noise-cancelling microphone (the Kruff Box) is not an adequate simulator of the aircraft noise environment.

Mayer and Lindburg (1981) proceed to describe their newly developed test procedures and communication system. The test consists of "real head" attenuation in pink noise with two microphones, one outside and one beneath the earmuff. The system, C-10414 ARC Intercommunication Control, has an increased bandwidth (300–4500 Hz) with a relatively flat response, and uses "expander/compander" circuitry, fast-acting automatic gain control, and a noise-cancelling microphone. This kind of research and development will be continued under a program entitled The Voice Recognition and Response for Army Aircraft (VRAA).

Microphones to enhance speech communication have been used for many years, with varying degrees of success. Perhaps one of the most effective versions is the noise-canceling microphone. Commonly known as the "close-talking" or "kiss-to-talk" microphone, it contains a port on either side of the diaphragm, so that random incidence sound waves will contact both sides of the diaphragm simultaneously and tend to cancel each other (Kryter, 1984). The speech signal will contact the diaphragm from only one direction and at close proximity, setting the diaphragm in motion. Other types of noise-reducing microphones include throat and ear microphones, which pick up the speech signal through body tissues. Their effectiveness is limited in high noise levels, however, because of bodily transmitted noise. Research will soon be conducted by the U.S. Air Force in which speech intelligibility will be tested using an array of about 18 microphones placed in the near field around the mouth (Nixon, personal communication, 1981).

1.3 TALKER AND LISTENER VARIABLES

1.3.1 Talker Variables

1.3.1.1 *Vocal effort and fatigue.* Although people readily raise their voices in a noisy background or when separated by distance, there is a limit to the length of time they can and will maintain an increased vocal effort. Pickett (1956) identified the highest level, measured at 1 meter, that could be sustained without painful voice fatigue as 90 dB, and, regardless of fatigue, the highest absolute level was 100 to 105 dB. However, as Webster and Klumpp (1962) have indicated, people will be reluctant to expend a vocal effort beyond 78 dB for more than a brief period of time, even in higher noise levels. They call this the "asymptotic speech level" (Webster & Klumpp, 1962).

Rupf (1977) assessed subjective estimates of the length of time people could talk in noise before their voices would become unduly strained. He found that on the basis of 5-min conversations in noise, about half the people believed they could talk for 1 hour in A-weighted levels of 75 dB, 30 min in 80 dB, 15 min in 85 dB, and 7 min in 90 dB. However, when asked to rate the feasibility of conversing during these 5-min segments, the 50% level of acceptability fell at an A-weighted level of 83 dB.

Discomfort is not the only adverse effect of talking in high noise levels. Reports of noise-exposed workers show an abnormally high incidence of vocal cord dysfunction (vocal nodules, chronic hoarseness, etc.) among workers who need to communicate as part of their work (Anonymous, 1979; Klingholz et al., 1978; Schleier, 1977). Klingholz, Siegert, Schleier, and Thamm (1978) found that 70% of laboratory subjects produced "pathological phonation" in A-weighted noise levels of 90 dB and above, and virtually all subjects did so in levels above 95 dB. Clinical evidence of vocal disorders in noise-exposed workers with speech-intensive jobs showed that the disorders tended to occur between the third and seventh year of work (Klingholz et al., 1978).

1.3.1.2 *Talker articulation.* The talker's speech patterns can have considerable influence on the intelligibility of speech. Common sense tells us that people with a foreign accent, strong regional dialect, or just generally sloppy articulation will be more difficult to understand than people with standard dialect and careful enunciation. Borchgrevink (1981) alludes to potential air traffic safety hazards when controllers speak in foreign accents, "with errors in phoneme pronunciation and prosodic features" (p. 15-3).

Little recent research on the effect of talker dialect is available, but two early studies tend to confirm the kind of concerns raised by Borchgrevink. Just after the end of World War II, Mason (1946) analyzed the speech recognition scores of nearly 2,000 young men from different Army commands throughout the United States. He found significant differences in speech intelligibility among the various regions, indicating that talkers from Northern commands had the most trouble understanding those from the Southern commands and vice versa. Although the author cautions that there were many potential sources of error, it appeared that the most intelligible talkers came from the Sixth Command, which included Michigan, Wisconsin, and Illinois, and the least intelligible came from the Eighth Command, encompassing Texas, Louisiana, Arkansas, Oklahoma, and New Mexico.

A later study by Black and Tolhurst (1955) examined the relative intelligibility of foreign and native dialects, and the effect of listeners' familiarity with each dialect. Subjects consisted of 12 French and 12 British pilot trainees and 24 American students, who recorded English monosyllables and then listened to them in a background of noise. The authors found that the British dialect was more intelligible than the French dialect to French as well as British listeners, and the French dialect was similarly intelligible (or unintelligible) to all three groups of listeners. Both the British and American listeners achieved higher scores with the American than with the British dialect. Also, practice with the unfamiliar dialect significantly improved speech recognition scores. These results do indicate potential problems for air traffic controllers, although it appears that practice would tend to mitigate unfavorable outcomes.

Other methods have also proved helpful in enhancing speech recognition. Picheny, Durlach, and Braida (1985) gave a short review of the benefits gained by training personnel to articulate clearly. They cite Snidecor, Malbry, and Hearsey (1944) as finding that drilling subjects to mimic the speech of a trained talker, as well as prompting them to talk louder, more clearly, and to open their mouths more, improved communication over military equipment. Similarly, Tolhurst (1955) was able to improve the intelligibility of speech in a noisy background by 10% when the talkers were instructed to speak more intelligibly. In another experiment, Tolhurst (1957) found that by either decreasing speech rate or by increasing clarity, he was able to improve intelligibility by as much as 9% (see Picheny et al., 1985).

Picheny and his colleagues (1985) studied the effects of conversational versus clear speech on listeners with impaired hearing. Listeners were presented short nonsense sentences via headphones at comfortable listening levels. When using the clear speech mode, talkers were instructed to enunciate consonants carefully, to avoid slurring words together, and to place stress on adjectives, nouns, and verbs. They were encouraged to talk as if they were speaking to a listener with hearing impairment in a noisy environment. Although listeners reported that the clear speech was tiring because it was spoken more slowly (sentences were approximately twice as long in the clear speech mode), the average improvement in intelligibility scores was 17%.

In a second article on the subject of clear speech, Picheny, Durlach, and Braida (1986) presented an acoustical analysis of clear speech and the differences between the clear and conversational speech modes. They found that the increase in clear speech duration is achieved by lengthening the individual speech sounds as well as by inserting or lengthening pauses. They also found that clear speech is characterized by the consistent articulation of stop-burst consonants, and all consonant sounds at the end of words, both voiced and unvoiced. Although changes in the long-term speech spectrum were small, the intensity for obstruent sounds (breath-obstructed) appears to be up to 10 dB greater in clear than in conversational speech. The authors note that to date there is no hard evidence that isolates the most important acoustical factors in differentiating between clear and conversational speech. Consequently, they suggest the development of a model that will permit the synthetic manipulation of variables known to be important. In this way, "one could gradually transform conversational speech into clear speech by varying one parameter at a time . . ." (Picheny et al., 1986, p. 444).

Because increases in duration appeared to be the most important factors in the intelligibility improvements gained by clear speech, Picheny, Durlach, and Braida (1989) examined the contribution of speaking rate to the intelligibility differences. The experiment involved processing conversational speech to conform in duration to clear speech and vice versa, using an algorithm that achieved rate changes without altering the fundamental frequencies of speech sounds. However, all listeners' scores decreased after both types of processing, indicating that uniform adjustments in speech duration would not achieve the improvements realized by clear speech. The authors point out that these decrements were not due to the processing because scores returned nearly to their previous levels when the speech materials were reprocessed to restore the original speaking rate. Picheny et al. concluded that research into nonuniform durational changes of the speech waveform would be necessary.

Mosko (1981) studied the effect of clear speech on radio voice communications with normal listeners. Listeners were trained to "over-articulate" for a period of 3 to 4 days. For speech material, Mosko chose digit sequences and words that commonly occur in aircraft communications, presented in quiet and in noise. Again, the duration of the clear speech segments was up to twice as long as the normal utterances, and intelligibility showed a 16% to 18% improvement in quiet. Preliminary data from the noise conditions showed an improvement of 6% to 8% at a speech-to-noise ratio of 0 dB. In the discussion following his paper, Mosko points out that the speech of people using radio communication systems tends to deteriorate over time.

> You can almost chart how long they have been on the job by the deterioration in their speech and you notice this time and time again. When you train people to use radios . . . they should be professional talkers (Mosko, 1981, p. 4–6).

1.3.1.3 *Gender.* There has been some controversy about the relative intelligibility of male and female voices. While the female voice is probably no less intelligible in most circumstances, it may be somewhat more difficult to understand in high noise levels when it is lower in sound energy. Pearsons, Bennett, and Fidell (1977) found the female voice to be 2 dB lower than the male voice in the "casual," "normal," and "raised" modes, 5 dB lower in the "loud" mode, and 7 dB lower in "shout." They maintained that their data did not support Beranek's (1954) recommendation that background noise be reduced consistently by 5 dB to accommodate female talkers. In a study of speech materials processed through Air Force communication systems, Moore, Nixon, and McKinley (1981) found small but systematic differences in the intelligibility of male and female voices in high levels of background noise. Although there was little difference at sound pressure levels of 79 and 95 dB, male voice intelligibility was 6.8% greater in 105 dB and 9.5% greater at a noise level of 115 dB. The authors were not sure whether this occurred because the high-frequency content of female speech was more easily masked, or because of the differences of vocal output with increasing levels of background noise.

1.3.2 Listener Variables

One of the most important variables in the perception of speech and warning signals is the hearing sensitivity (or lack of hearing sensitivity) of the listener. It includes not only hearing loss from noise, but also from other etiologies, including presbycusis, which is the hearing loss resulting from the aging process. This topic will be discussed in detail in Chapter 2 of this monograph.

1.3.2.1 *Preferred listening levels.* Although quite high levels of speech can be tolerated with little or no loss of intelligibility if the speech is amplified and if the speech-to-noise ratios are sufficiently high, people prefer to listen to speech within a certain range of levels. A study by van Heusden et al. (1979) explores the relationships between selected listening levels in the sound field for speech and background noise. Using a Bekesy "up-down" adjustment method, listeners were instructed first to find the preferred speech level, as if listening to a radio, and later to find the minimum required level for understanding speech. (No details are given for the criteria for "understanding.") Speech and speech-shaped noise were presented through separate loudspeakers. A-weighted noise levels were 40, 50, 60, and 70 dB and quiet. The results showed average preferred speech levels of 49 dB(A) in quiet, and 61 dB(A) in noise, with a slope of 3.1 dB per 10-dB increase in background noise level—above about 35 dB(A). "Minimum" speech levels were identified as 25 dB(A) in quiet, and about 54 dB(A) in the 70-dB(A) noise condition, with a slope of 6.4 dB per 10-dB increase in noise level above 40 dB(A). The investigators concluded that people prefer to keep about the same (subjective) loudness level of speech in noise as they experienced in quiet, although this level will not guarantee the same level of intelligibility.

In a follow-up study by Pols, van Heusden, and Plomp (1980), the same group of experimenters studied preferred listening levels for speech as a function of modulation frequency in fluctuating noise. Experimental conditions were similar, except that the noise, which was typical of community noise, was modulated at frequencies of 0.1, 0.3, 1, and 5 Hz. Also, subjects used a slightly different psychophysical method, which gave them somewhat more time in which to make their selections. The results showed that modulation frequency had a negligible effect on the selection of preferred listening level, so long as the equivalent sound level was constant among noise stimuli. However, the identified preferred levels were about 10 dB higher than in the previous experiment, and the slope of the curve was 5 dB per 10-dB increase in noise level above 35 dB(A), rather than 3.1 dB. Pols and his colleagues offer no explanation for the difference in slope, but they believe that the difference in level may be due to the difference in adjustment methods. In this experiment, the method may have led to the identification of the *most* comfortable listening level, whereas in the previous experiment the levels identified would have reflected the *just* comfortable level. Pols et al. hypothesize a similar explanation for other such discrepancies they noted in the literature. This leads them to conclude that preferred listening levels are better described by a range of levels than by single numbers.

Investigations of preferred listening levels under earphones have produced somewhat higher levels, but there is considerable variation among studies. Beattie (1982) measured most comfortable listening levels (MCL) in quiet, and in white noise levels of 55, 70, 85, and 100 dB SPL. The slope of the MCL, 5.3 dB per 10-dB increase in noise level, was similar to that of Pols et al. (1980), but the mean identified levels were much higher: 82.5 dB in quiet, and 90.9 dB and 100.3 dB in noise levels of 85 dB and 100 dB respectively. Beattie and his coworkers point out that there is a wide range of MCLs reported in the literature, varying from a low of 42 dB SPL in a study by Schaenman (1965) to a high of 91 dB found by Loftiss (1964). The discrepancies seem to be due mainly to differences in instructions and psychophysical methods of threshold determination (Beattie, 1982). One factor that would account for a portion (about 6 dB) of the difference between the results of Beattie and the work of van Heusden et al. (1979) and Pols et al. (1980) is the difference in thresholds of sensitivity between listening in the sound field and under earphones. Another factor would be the use of A weighting by van Heusden and Pols, which would account for an additional 4 dB when compared with unweighted sound pressure levels, and still another is the use of higher noise levels by Beattie, which would be likely to induce listeners to raise speech levels.

In the above experiments, subjects were presented with a fixed level of noise and were permitted to adjust the preferred listening level separately. In a subsequent experiment (Beattie & Himes, 1984), subjects were presented with a fixed speech-to-noise ratio (under earphones) and asked to identify MCLs, adjusting the speech and noise together, as they would when listening through a hearing aid or a communication system. The investigators found MCLs that ranged from 78 dB SPL in a speech-to-noise ratio of −10 to 83 dB SPL in a speech-to-noise ratio of +10. Upper ranges of comfort, defined as the point at which listening would be uncomfortable if the level were any louder, were 93 dB SPL for a speech-to-noise ratio of −10, and 98 dB SPL in quiet. Although there was a great deal of individual variability, it is interesting to note that people will include higher levels of speech within the comfort zone as long as they do not have to content with too much noise.

1.3.2.2 *Non-native listeners.* Degraded communication can occur when listeners, as well as talkers, use a language that is not their native tongue. Using short, high-predictability and low-predictability sentences (the SPIN test), Florentine (1985) tested 11 native and 14 non-native but fluent-in-English listeners. She found that the native listeners were able to obtain 50% performance levels at significantly lower speech-to-noise ratios (about 3 dB) than the non-native listeners. Likewise, Nabelek (1983) found differences between native and non-native listeners as a function of reverberation. In a reverberation time of 0.4 sec, non-natives scored 6% lower than native listeners, and with reverberation times of 0.8 to 1.2 sec, they scored 10% lower.

In an interesting study of the effects of listening in a second language, Borchgrevink (1981) selected 13 Norwegian men who were fluent in English and 13 Englishmen fluent in Norwegian, and tested them with "everyday" Norwegian and English sentences, balanced and matched for syntax and phoneme frequency. The subjects listened to these sentences at 65 dB SPL in the sound field, in a noise background that was decreased between sentence sets in 2-dB steps from 76 to 56 dB SPL. The results showed that both the Norwegian and English subjects needed significantly more favorable speech-to-noise ratios when listening in their second language (see Table 1).

The author notes that individuals need fewer acoustical cues to understand sentences presented in their first language, even when they are fluent in the second language. He concludes that subjects are better equipped to synthesize a degraded message in their native language because of a more firmly established "concept-reference coherence" (Borchgrevink, 1981).

1.3.2.3 *Speech recognition during a secondary task.* Although the literature on the subject is not extensive, it appears that noise has an added disruptive effect when the listener must comprehend speech and perform another task simultaneously. Lazarus (1983) presents data from Hormann and Ortscheid (1981) showing that speech recognition scores decrease as a function of speech-to-noise ratio more rapidly when a visual memory task is added. Jones and Broadbent (1979) cite other investigations indicating that subjects trying to understand speech in noise have difficulty remembering material learned in quiet (Rabbitt, 1966, 1968). They describe an earlier experiment by Broadbent (1958) in which subjects were presented both with speech in noise and with speech filtered as if it were masked by noise. Although there was no significant difference in speech recognition scores, there was a deficit in a secondary tracking task in the noise condition that did not occur in the filtered speech condition. The authors conclude that the extended effort required to cope with the noise produces a penalty in other activities (Jones & Broadbent, 1979).

1.3.2.4 *Auditory fatigue.* In this context, auditory fatigue may mean temporary threshold shift (TTS) or a more central effect "analogous to perstimulatory fatigue or loudness adaptation" (Pollack, 1958). Regardless of the etiology, high noise or speech levels may produce a deterioration in speech recognition with continued exposure.

Pollack (1958) investigated the effects of broadband noise and speech levels (S/N = 0 dB) of 110 dB to 130 dB

TABLE 1. Speech-to-noise ratios needed for correct repetition of sentences (From Borchgrevink, 1981).

	S/N needed by Norwegian subjects		*S/N needed by English subjects*	
	M	*SD*	*M*	*SD*
Norwegian sentences	0.1	1.28	3.9	2.66
English sentences	2.1	1.66	0.4	1.36

for successive 100-sec exposures. Speech recognition scores deteriorated significantly over successive tests at noise and speech levels above 115 dB, and the deterioration in time was roughly logarithmic over the period of the eight tests. Not unexpectedly, post-stimulatory tests showed large decrements in speech recognition for soft (45 dB) and very loud (125 dB) speech, but no significant effects on speech in quiet between these levels (Pollack, 1958).

In another study of the effects of auditory fatigue, Parker, Martens, and Johnston (1980) exposed subjects to a 1500- to 3000-Hz band of noise at 115 dB for 5 min. After noise exposure, recognition scores for PBs in a 2825- to 3185-Hz band of noise were poorer in quiet, slightly poorer in the 90-dB noise condition, about the same in 40 dB, and somewhat better in the 65-dB noise condition. The authors conclude that the subjects responded as predicted from a "recruitment model" (referring to the improvement in the 65-dB noise condition), and suggest that a small TTS would not affect speech embedded in moderately intense masking noise.

Sorin and Thouin-Daniel (1983) studied the effects of mild TTS on the recognition of low-level speech in noise (speech at 34 dB(A), noise at 40 dB(A)). They added a "lexical decision" task in the form of a word/nonword judgment, in an attempt to test central as well as peripheral dysfunction. The results showed that the presence of a 15-dB TTS produced an increase from 5.3% to 10.8% incorrect rhyme words and 5% to 13.5% incorrect lexical responses (which includes decisions exceeding a 2-sec limit). They also noticed that the presence of TTS increased a subject's tendency to respond "word" more often than "nonword," a type of response that has been identified in studies of the effects of noise on task performance. Although speech at 34 dB(A) is not typical of everyday conversation, it could characterize certain combat conditions, where understanding softly spoken messages is of vital strategic importance.

1.4 PREDICTION METHODS

1.4.1 Articulation Index

The Articulation Index (AI) is a method for predicting the efficacy of speech communication in noise, based on the research and method of French and Steinberg (1947). The classic "20 band" method uses measurements or estimates of the spectrum level of speech and noise in 20 contiguous bands, each of which contribute equally to speech intelligibility. This method has been improved and modified by Kryter and his colleagues for numerous conditions of noise and distortion (see Kryter, 1962a, and ANSI, 1969). These modifications include the following:

1. Corrections for reverberation times up to 9 sec.
2. Corrections to the noise spectrum for spread of masking effects (upward, downward, and nonlinear growth).
3. Methods using octave and ⅓ octave bands instead of the original 20 bands.
4. Calculation of AI for non-steady-state noise with a known duty-cycle and levels that fall at least 20 dB during the "off period."
5. Calculation of AI for nonsteady noise when the rate of interruption is known.
6. Adjustments for the effects of sharp, symmetrical peak clipping.
7. Corrections for vocal effort, including speech levels of 40 to 100 dB (long-term rms).
8. Corrections for the added benefits of lipreading.

Applications of the AI to listeners with impaired hearing have been suggested by Braida et al. (1979), Dugal, Braida, and Durlach (1980), Humes, Dirks, Bell, Ahlstrom, and Kincaid (1986), Kamm, Dirks, and Bell (1985), Kryter (1970), and Skinner and Miller (1983).

Although the AI can be somewhat complicated in terms of measurement and instrumentation, it has been found to be a valid predictor of speech intelligibility in a variety of conditions (Kryter, 1962b), and has been a popular and a respected measurement tool over recent decades.

1.4.2 Speech Interference Level

Originally developed by Beranek (1954), the Speech Interference Level (SIL) provides a quick method of estimating the distance with which communication can occur for various levels of vocal effort. The current method involves taking the arithmetic average of sound levels in the octave bands 500, 1000, 2000, and 4000 Hz. According to ANSI S3.14 (ASA, 1977), the primary purpose of the SIL is to rank-order noises with respect to speech interference. Figure 5, from ASA (1977), shows talker-to-listener distances for "just reliable" communication (defined as 70% monosyllables), with the approximate A-weighted level on the abcissa for comparison. "Expected voice level" reflects the natural increase in vocal effort with increasing SIL.

Figure 6 shows Webster's most recent version of the SIL criteria (Webster, 1983), with numerous modifications and embellishments. Webster (1983), describes them as (a) a broader range of voice levels to reflect differences between public and private voice levels (see Houtgast, 1980; van Heusden et al., 1979); (b) a different rate of fall-off of speech level with distance based on typical room reverberation; (c) "equivalent noise floors" based on room reverberation (see Houtgast, 1980); and (d) a downward shift of 3 dB in the voice level reference lines at 1 meter to account for the differences between A-weighted and rms speech levels (according to Steeneken & Houtgast, 1978). Despite all of these modifications, the SIL still has certain disadvantages in that it assumes normal hearing on the part of the listener and face-to-face communication with unexpected word material (Webster, 1984), and it uses only one level of intelligibility (70% monosyllables). Someone who desired 90% word intelligibility, for example, would not be able to use the chart.

1.4.3 Speech Transmission Index

Developed by a group of researchers at the TNO Institute for Perception in the Netherlands, the Speech Trans-

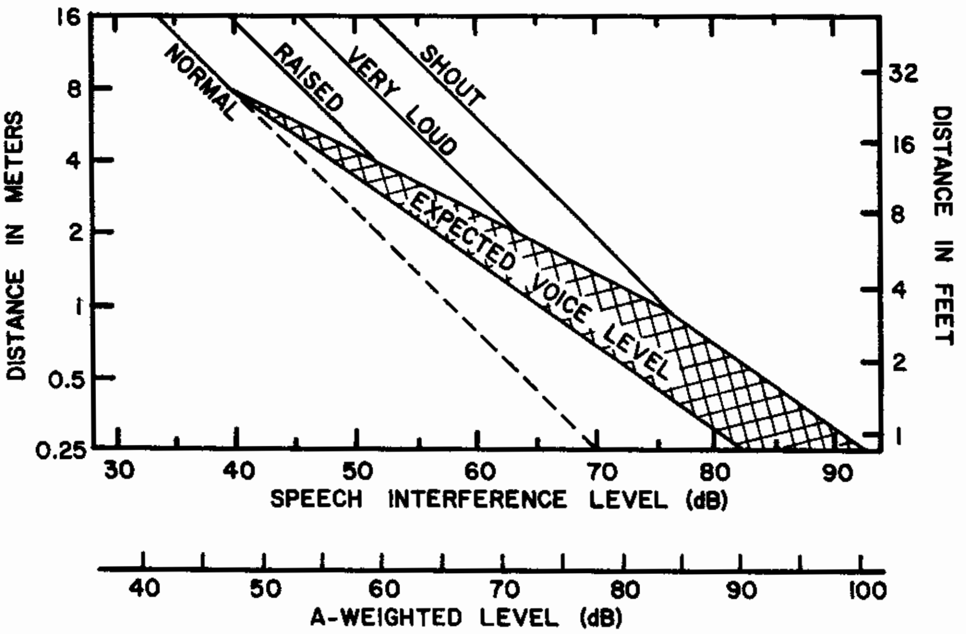

FIGURE 5. Talker-to-listener distances for just-reliable communication. (ANSI, 1986. Reprinted by permission.)

mission Index (STI) is derived from a speech transmission channel's "Modulation Transfer Function" (MTF). The MTF may be measured with special equipment or calculated from the volume and reverberation time of the room, distance between talker and listener, and noise level (Houtgast, 1980). Figure 7 from Houtgast (1980), shows a model of the derivation of the STI. Houtgast gives data indicating an excellent correlation between STI and speech intelligi-

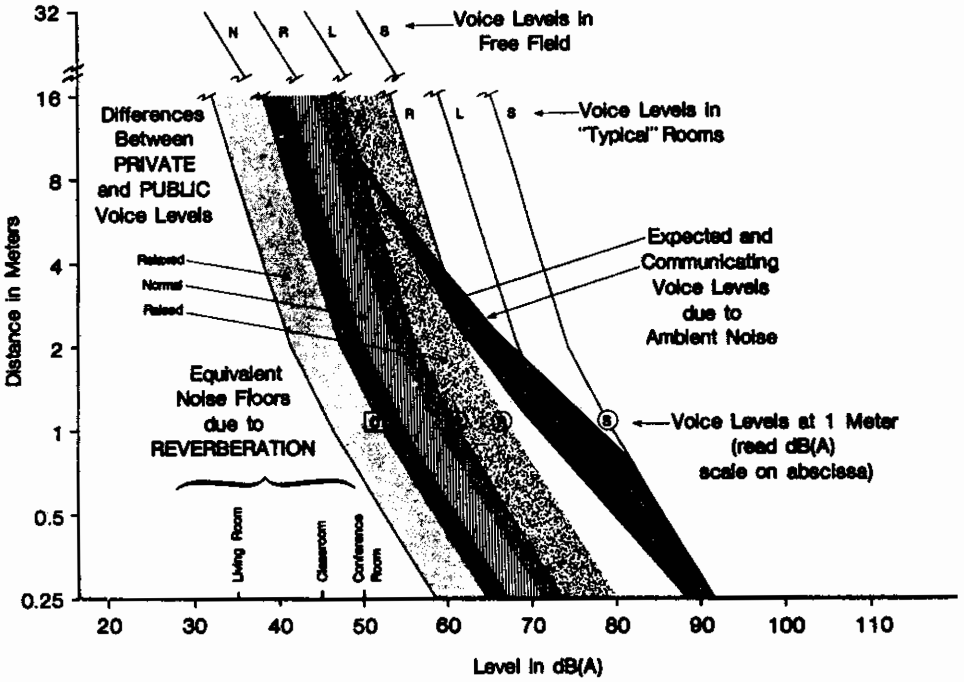

FIGURE 6. Revised "SIL" chart showing relationships among A-weighted ambient noise levels, distances between communicators, and voice levels of talkers for just-reliable communication indoors. (Webster, 1983. Reprinted by permission.)

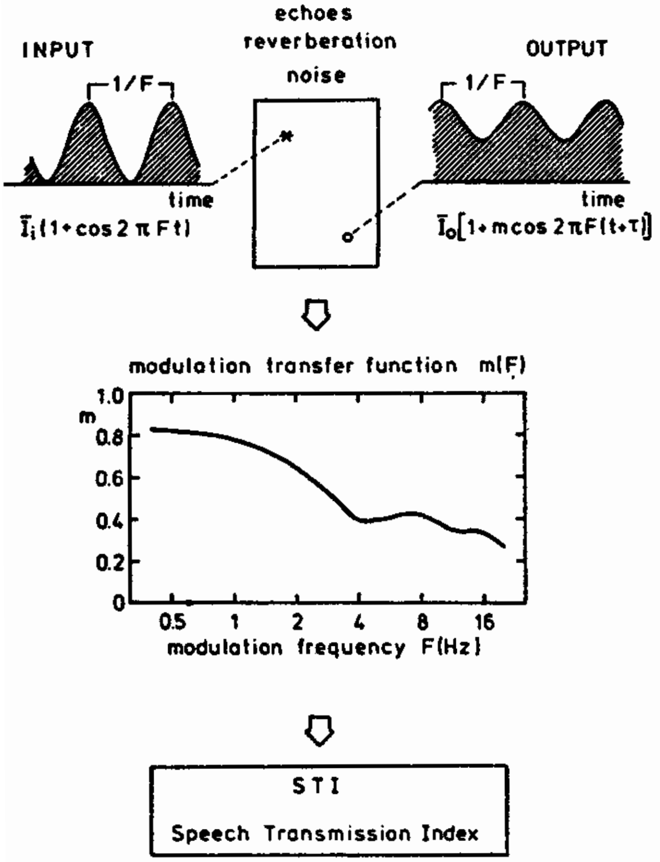

FIGURE 7. Derivation of the Speech Transmission Index. (ASHA, 1980. Reprinted by permission.)

bility for a wide variety of large rooms. The author also explains that in a highly reverberant room, noise below a certain level can have no degrading effect on speech because the adverse effects of reverberation dominate. This is the "noise floor," which Webster has incorporated in his latest SIL chart (see Figure 6).

In a later paper, Houtgast and Steeneken (1983) discuss the verification of the original model, which had used only speech-shaped noise, reverberation, and Dutch monosyllables. Subsequent research showed the STI to be a good predictor of speech intelligibility (a) in five types of noise spectra; (b) with other distortions besides reverberation, such as filtering, peak-clipping, and automatic gain control; (c) with untrained subjects outside the laboratory; (d) for sentences in addition to monosyllables; and (e) for seven other languages besides Dutch (Houtgast & Steeneken, 1983).

Humes et al. (1986) modified the STI by analyzing spectral information from the speech and noise signals in ⅓ octave rather than octave bands, and by weighting the bands according to the method originally developed by French and Steinberg (1947) for the AI. Humes and his colleagues found that these adjustments improved the STI's ability to predict speech recognition scores in both normal-hearing and hearing-impaired listeners.

In a subsequent effort, Humes, Boney, and Loven (1987) tested their modified STI (mSTI) on a large set of existing speech recognition data obtained under a variety of conditions, including low-pass and high-pass filtering and various speech levels and speech-to-noise ratios. They found that the mSTI was a good predictor of speech recognition in all conditions, with the exception of low-pass filtering. The investigators speculate that increasing the frequency resolution of the mSTI (and AI) from 15 to 20 bands might solve this problem.

1.4.4 Sound Level Meter Weighting Networks

In addition to the fact that the sound level meter with its A-weighting network is inexpensive, readily available, and easy to use, it is a good predictor of speech interference, especially in noise spectra that are not unduly complex. Klumpp and Webster (1963) found A-weighting far superior to the other weighting networks, and Webster has effectively substituted A-weighting for SIL in his latest "SIL" chart (see Figure 6). Measuring the noise, however, gives only part of the information of interest. The A-weighting network can also be used effectively to predict AI and STI by measuring both speech and noise levels to obtain a speech-to-noise ratio. In addition, Webster (1984) also points out that A-weighting is amenable (as are all weighting networks) to time integration. Second to the AI, CHABA Working Group 83 recommends the A-weighted L_{eq} for predicting the effects on speech intelligibility of time-varying noise (CHABA, 1981).

Based on an analysis of 16 equally speech-interfering Navy noises (Klumpp & Webster, 1963), Webster (1964) developed a set of speech-interference (SI) contours that could serve as sound level meter weighting networks. In this process, Webster found that as the AI (and consequently speech intelligibility) increased, the frequencies that most effectively mask speech increase from about 800 Hz to around 3000 Hz (Webster, 1964). Figure 8 shows Webster's SI curves, including two curves originally developed by Beranek (1957). The S-I 50 curve is appropriate for an AI of 0.8, the S-I 60 for an AI of 0.5, S-I 70 for an AI of 0.2, and the S-I 80 for an AI of up to 0.05. Although these curves have never been incorporated into standard sound level meters, they seem to offer some interesting possibilities.

1.4.5 Relationship of Methods to One Another

These predictive methods can be viewed together with respect to their physical interrelationships and to their relative merit as predictors. ANSI S3.14 (ASA, 1977) states that for many common noises, the SIL (yielding 70% intelligibility) will be about 8 dB below the A-weighted sound level. According to ANSI S3.5 (ANSI, 1969), 70% monosyllable intelligibility (for 1000 PBs) is achieved at an AI of 0.45, which translates to an approximate speech-to-noise ratio of 1.5 dB. For speech-shaped noise, the STI and AI have a uniform and predictable relationship. A speech-to-noise ratio (S/N) of 1.5 dB corresponding to an AI of 0.45 will yield an STI of 0.55 (see Houtgast, 1980). This relationship can be seen as follows:

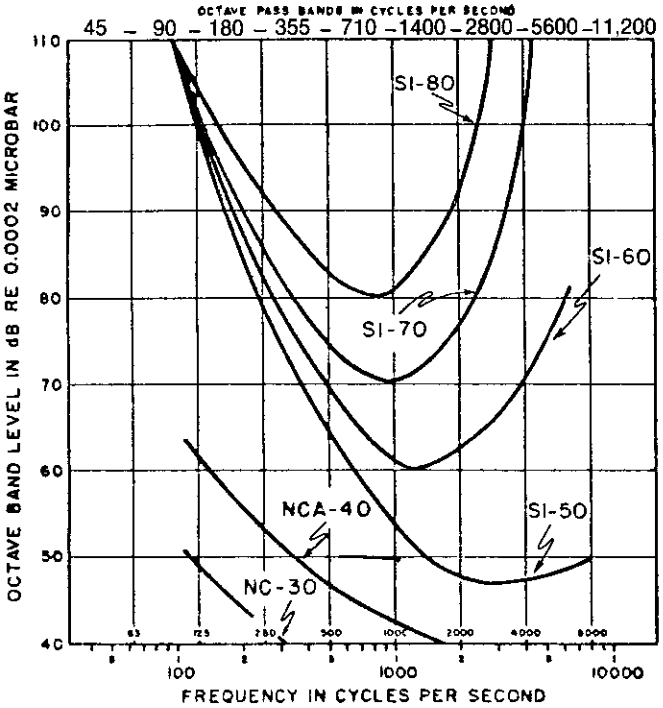

FIGURE 8. Webster's suggested speech interference (SI) contours, including two noise criteria curves from Beranek. (Webster, 1964. Reprinted by permission.)

$$AI = (S/N)/30 + 0.4$$

$$STI = (S/N)/30 + 0.5$$

To assess the effectiveness of various rating schemes, Klumpp and Webster (1963) compared AI, dB(A), two versions of the SIL, and various other measures in 16 equally interfering Navy noises. They found that the AI showed the least variability, followed by the SIL 355–2800 Hz, dB(A), and SIL 600–4800 Hz. Kryter and Williams (1965) found that the SIL 600–4800 Hz outperformed the SIL 355–2800 Hz in aircraft noises, which generally contain a greater proportion of high frequencies than the Navy noises.

In a recent study, Bradley (1986) compared four methods for predicting speech intelligibility in medium-sized to large rooms: AI, A-weighted speech-to-noise ratio, STI, and Lochner and Burger's (1964) "useful/detrimental" sound ratios. In this latter method, useful energy is defined as the weighted sum of energy arriving in the first 0.095 second after the arrival of direct sound. Detrimental energy is any later-arriving energy from the speech source plus background noise in the room (Bradley, 1986). The results showed that all methods did reasonably well, but the Lochner/Burger method produced the highest correlation with speech intelligibility and the lowest error. The AI and A-weighted speech-to-noise ratio performed nearly as well, and the STI ranked fourth in effectiveness. The author concludes that a satisfactory and simple approach would be to measure the A-weighted speech-to-noise ratio and the reverberation time at 1000 Hz, and use the regression coefficients he developed to form prediction equations (see Table I and Figure 9 in Bradley, 1986).

1.5 ACCEPTABILITY CRITERIA

1.5.1 Minimal or "Just Reliable" Communication

There is a paucity of information on the subject of communication requirements for specific activities. Quite a few investigators refer to minimum requirements for "just reliable" communication, but few elaborate on the uses of this level of communication or on the amount of communication needed for various purposes. Most agree that the minimum conditions to barely communicate range from an AI of 0.3 to 0.45. Table 2 gives recommendations for "just reliable" communication conditions from five sources. Data actually mentioned by the sources are underlined, and the remaining data have been filled in with the help of ANSI S3.5 (1969) (see Figure 3).

Although ANSI S3.5 gives no specifications for "just reliable" communication, the standard states the following:

> What level of performance is to be required over a given system is, of course, dependent upon factors whose importance can be evaluated only by the users of the communication system. Present-day commercial communication systems are usually designed for operation under conditions that provide AI's in excess of 0.5. For communication systems to be used under a variety of stress conditions and by a large number of different talkers and listeners having varying degrees of skill, an AI of 0.7 or higher appears appropriate. (ANSI, 1969)

1.5.2 Recommendations for Various Environments and Operations

Although the literature is virtually silent on the specific amount and type of communication needed for various operations, numerous recommendations exist for background sound levels that are appropriate for certain activities and spaces. For example, the German government recommends the following "rating level" (A-weighted L_{eq} with corrections for impulses and tones): maximum of 55 dB for jobs that involve mental activity, maximum of 70 dB for simple and mechanized office activities, maximum of 85 dB for all other activities (Lazarus, 1983). According to the U.S. Environmental Protection Agency (EPA, 1974), A-weighted background noise levels of 45 dB will allow 100% intelligibility of relaxed conversation indoors, and 95% sentence intelligibility is achieved at a level of about 64 dB.

Table 3 shows recommendations from Beranek, Blazier, and Figwer (1971) for "preferred noise criterion" (PNC) curves and A-weighted background noise levels to achieve various levels of communication in various types of spaces. Levels of 66 to 80 dB are recommended for work spaces where communication is not required. For the others, the recommendations range from 56 to 66 dB for "just acceptable" speech and telephone communication in shops, garages, power-plant control rooms, and so forth, to 21 to 30

TABLE 2. Conditions for "just reliable" communication.

Source	*AI*	*S/N*	*STI*	*Monosyllable intelligibility*	*Sentence intelligibility*	*Author's comment*
Beranek (1947)	0.3	−3 dB	0.4	43%[a]	80%[b]	Unsatisfactory or marginally satisfactory.
ANSI S3.14 (ASA, 1977)	0.45	1.5 dB	0.55	70%[a]	95%[b]	Just reliable.
Houtgast (1980)	0.4	0 dB	0.5	62%[a]	93%[b]	Just reliable.
CHABA (1987)	0.35	−1.5 dB	0.45	54%[a]	88%[b]	Lower range of "fair."
Webster and Allen (1972)[c]	0.35	−1.5 dB	0.45	80%[d]	95%	Minimum acceptable for certain military communication equipment operating in "highly adverse" conditions.

Note. Underlined data are those identified by sources. Other data estimated using Figure 1.3 (Figure 15 in ANSI, 1969).
[a] 1000 PB words. [b] Unfamiliar sentences. [c] Cited in Webster, 1978. [d] Fairbanks Rhyme Words.

dB for excellent listening conditions in large auditoriums and concert halls.

The National Aeronautics and Space Administration (NASA) asked the National Academy of Sciences/National Research Council's Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) to draft criteria for speech communication aboard the future NASA space station (CHABA, 1987). In their report, the authors assume A-weighted speech levels of 62 dB in the direct field and 60 dB in the indirect field (greater than 1 meter), where most of the communication would take place. To obtain a minimum speech-to-noise ratio of 5 dB, the maximum noise level should be 55 dB(A). Assuming a 1-sec reverberation time, this translates to an STI of 0.45, an AI of 0.35, and sentence intelligibility of 88% (see Table 2). The authors mention a recommended range of STIs from 0.45 to 0.6, which would yield sentence intelligibility of up to 95% (CHABA, 1987). Presumably, however, for an STI of 0.6, either the reverberation time would have to be reduced or the speech-to-noise ratio should be considerably higher.

1.5.3 Consequences of Degraded Speech

Although the consequences of degraded speech can be extremely serious, most of the references in the literature are anecdotal or subjective. Although these kinds of findings lack the power of objective, quantified research results, they are nevertheless compelling. For example, Williams and his coauthors state, "Field reports have indicated situations wherein troops emplaning from rotary-wing aircraft sometimes experience hearing threshold shifts of such severity that they are unable to make use of aural cues in detecting enemy movements" (Williams, Forstall, & Parsons, 1970, p. 1).

At a conference entitled Aural Communication in Aviation, sponsored by the Advisory Group for Aerospace Research and Development (AGARD), some of the contributors alluded to the consequences of degraded speech. Mayer and Lindberg (1981) pointed out that future battles will be fought on or near the ground in a "nap of the earth" environment. This will increase the aviator's already heavy workload. The fatiguing effects of high noise and poor communication will have adverse effects on aviators' combat effectiveness (Mayer & Lindburg, 1981). Conference Chairman Money referred to the "significance of failure or inadequacy of speech communication or audio warning systems in military operations . . ." and the consequent "cost in training and reduction of operational effectiveness" (Money, 1981, p. ix). In a discussion of clear speech later in the meeting, McKinley (1981) remarked:

> Your reference to standard language has prompted me to make these remarks about something I have found in examining tapes of last messages from pilots during accidents. It is that usually, the message is a short unfamiliar language and in many cases, unintelligible. I think they could have been intelligible if the system had been designed correctly.

One study that simulates the consequences of communication failures in terms of error rates is the study of speech recognition using the M25 gas mask by Garinther and Hodge (1987). The authors cite the Defense Department's MIL-STD-1472C (DoD, 1981) defining "minimally acceptable" communication as a PB score of 43%, and "normally acceptable" communication as a PB score of 75%. Gas mask wearers were unable to achieve the 75% level at a distance of only 1 meter, and the 43% "minimal" level was achieved at a distance of 12.5 meters. Unmasked listeners could achieve this level at approximately 48 meters. Garinther and Hodge note that 12.5 meters is about one half the distance at which platoon leaders would like to be able to communicate in field conditions. On the basis of their data, they estimate that using maximum vocal effort at a distance of 12.5 meters, individuals wearing gas masks would have an error rate of 3% with a small set of standard words, 7% with standard, previously known sentences, and 20% with nonstandard sentences. One could expect an even higher error rate for nonstandard words out of context. Garinther and Hodge also point out that maximum vocal effort can be sustained for only a short period of time.

Any system that allows less than 100% intelligibility assumes that some words will be lost or misunderstood. Systems that are designed for "just reliable" or "fair" communication depend for an extra margin of safety upon the normal redundancy of sentences, and especially upon the added redundancy provided by standard phraseologies, such as air traffic control language. These systems will function relatively effectively under normal conditions. However, normal conditions may be disrupted by any number of causes: an emergency requiring a nonstandard word;

Table 3. Recommended preferred noise criteria (PNC) and A-weighted levels for steady background noise in various indoor areas.

Type of space (and acoustical requirements)	*PNC curve*	*Approximate L_A, dBA*
Concert halls, opera houses, and recital halls (for listening to faint musical sounds)	10 to 20	21 to 30
Broadcase and recording studios (distant microphone pickup used)	10 to 20	21 to 30
Large auditoriums, large drama theaters, and churches (for excellent listening conditions)	Not to exceed 20	Not to exceed 30
Broadcast, television, and recording studios (close microphone pickup only)	Not to exceed 25	Not to exceed 34
Small auditoriums, small theaters, small churches, music rehersal rooms, large meeting and conference rooms (for good listening), or executive offices and conference rooms for 50 people (no amplification)	Not to exceed 35	Not to exceed 42
Bedrooms, sleeping quarters, hospitals, residences, apartments, hotels, motels, etc. (for sleeping, resting, relaxing)	25 to 40	34 to 47
Private or semiprivate offices, small conference rooms, classrooms, libraries, etc. (for good listening conditions)	30 to 40	38 to 47
Living rooms and similar spaces in dwellings (for conversing or listening to radio and TV)	30 to 40	38 to 47
Large offices, reception areas, retail shops and stores, cafeterias, restaurants, etc. (for moderately good listening conditions)	35 to 45	42 to 52
Lobbies, laboratory work spaces, drafting and engineering rooms, general secretarial areas (for fair listening conditions)	40 to 50	47 to 56
Light maintenance shops, office and computer equipment rooms, kitchens, and laundries (for moderately fair listening conditions)	45 to 55	52 to 61
Shops, garages, power-plant control rooms, etc. (for just acceptable speech and telephone communication). Levels above PNC-60 are not recommended for any office or communication situation	50 to 60	56 to 66
For work spaces where speech or telephone communication is not required, but where there must be no risk of hearing damage	60 to 75	66 to 80

Note. From Beranek, L. L., Blazier, W. E., & Fegwer, J. J. (1971). Preferred noise criterion (PNC) curves and their application to rooms. *Journal of Acoustical Society of America, 50,* 1223–1228. Reprinted by permission.

a sudden decrease in speech-to-noise ratio; a momentary equipment failure; or a "panic" situation in which intelligibility is drastically reduced. The consequences of inadequate or misunderstood instructions in these situations can be dire indeed: in the extreme, loss of life and destruction of expensive equipment.

1.6 DETECTION OF WARNING SIGNALS IN NOISE

Noise can mask warning sounds in the same way it masks speech. Theoretically, a warning sound will be audible if any frequency in the sound exceeds the critical ratio with respect to the surrounding band of noise. But the fact that the signal is detectable does not necessarily mean it will be effective. In the development of criteria for audible warning signals, Wilkins and Martin (1982) differentiate between detectability, demand on attention, and recognizability of signals. They point out that inattention may elevate the masked thresholds of warning signals (over the threshold of detectability), and that an even greater signal-to-noise ratio could be necessary when the signal is embedded among other meaningful, but irrelevant stimuli. These investigators cite a level of at least 15 dB above masked threshold as a widely accepted safety margin, and advocate a signal-to-noise ratio of at least 18 dB for 100% detectability, especially if hearing protection is used (Wilkins & Martin, 1982).

Coleman et al. (1984) concur with the need for a 15-dB difference between signal level and masked threshold to produce "clear audibility" (p. 21). They maintain that as the signal approaches this level the listener will regain perceptual abilities and the ability to localize the direction of the signal source. But the 15-dB difference does not guarantee the signal's ability to claim the subject's attention.

The National Fire Prevention Association asked CHABA to develop a national fire alarm signal (Green et al., 1975). The criteria were that the signal must be easily detected above background noise, different from other alarm signals, and adaptable to existing systems. The CHABA working group recommended a standard temporal profile, consisting of two short bursts and a long burst. Nominal on segments should be between 0.4 and 0.6 sec and off segments between 0.3 and 0.6 sec, with a rise and decay of 10 dB within 0.1 sec. The on state should exceed the listener's 24-hour L_{eq} by 15 dB, and should exceed by 5 dB any maximum level for which the duration is greater than 30 sec. The working group cautioned users not to exceed a level of 130 dB without "consultation with local health authorities."

More recently, the ISO issued a standard entitled Audible Emergency Evacuation Signals, dealing only with temporal pattern (ISO, 1987). The standard calls for a train of three short pulses. Each pulse is 0.5 sec in duration and is followed by a pause of 0.5 sec. The pulse train is then followed by a pause of 1.5 sec, after which the pattern is repeated. Level and spectrum are to be determined by the user. This standard was adopted in the United States as ANSI S3.41-1990 (ASA, 1990).

In a very thorough and well-researched effort, Patterson (1982) offers a set of guidelines for auditory warning systems for civil aircraft. He has identified numerous problems with existing civil aviation warning systems:

1. The warning levels are too loud. "They flood the flight-deck with very loud, strident sounds," disrupting thought patterns and communication, and making the systems unpopular with the crews (p. 1).
2. Temporal characteristics are unsatisfactory. The onsets and offsets are sufficiently abrupt to evoke startle reactions, the temporal patterns are not sufficiently distinctive, and the total on-times are too long, interfering with speech communication.
3. Low priority warnings sometimes appear to be more urgent than high priority warnings.
4. The ergonomics of these warning systems are "deplorable." They are lacking in a sense of perspective, meaning that many are false and others have confused priorities. The aversive character of the sound is likely to convince the crew to cancel it as quickly as possible, thereby canceling the protection it provides.
5. Voice warnings are not frequently used, and the speech quality of existing systems is not good.

To correct these defects, Patterson developed a prototype warning system based on a comprehensive research effort. The following guidelines resulted:

1. Overall level should be at least 15 dB and not more than 25 dB above masked threshold.
2. The temporal pattern should consist of pulses with 20 to 30 msec rise and decay times, and gating functions that are rounded and concave downward. Pulse duration should be 100 to 150 msec, and intervals between pulses should be less than 150 msec for urgent and greater than 300 msec for nonurgent warnings. Each warning burst should consist of a set of 5 or more pulses in a distinctive temporal pattern.
3. The spectrum should consist of 4 harmonically related components between the frequencies of 500–5000 Hz, with a fundamental frequency between 150 and 1000 Hz. Signals demanding immediate action should contain a few quasiharmonic components and/or a brief frequency glide.
4. For ergonomic reasons, manual volume control should be avoided, and AVC should be restricted to a 10–15 dB range. The total repertoire of signals should consist of not more than six immediate-action signals and up to three "attensons" (less urgent but attention-demanding sounds such as musical chords).
5. Voice warnings for immediate action should be brief, without repetition, and in a key-word format. Less urgent warnings can be full-phrase and can be repeated. The system should accommodate a frequency range of 500 to 5000 Hz, and there should be progressive amplification of 3 dB/octave between those frequencies.

Figure 9 gives the component patterns for an "advanced" warning signal developed by Patterson (1982), showing four regularly spaced pulses followed by two irregularly spaced pulses. Sound level is reflected by the ordinate, and time is on the abcissa. Rows 3 and 4 show increasing levels of urgency. Figure 10 also from Patterson (1982), shows the time course of a complete warning. Each little trapezoid represents a series of pulses as in Figure 9, and the relative intensities are reflected by trapezoid height. This warning includes the voice message "undercarriage unsafe."

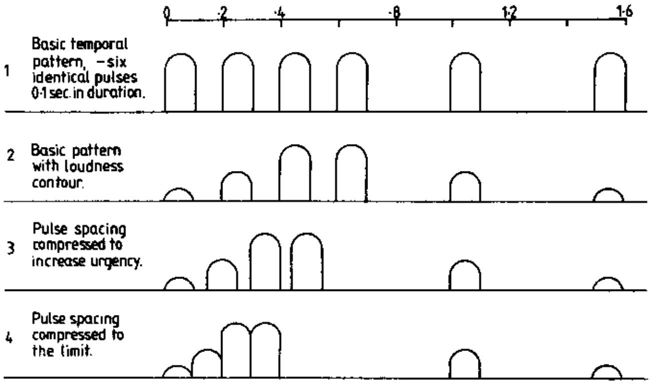

FIGURE 9. Component patterns for an advanced auditory warning signal. (Patterson, 1982. Reprinted by permission.)

Subsequent to their development, Patterson's guidelines have been used with both conventional and rotary-wing aircraft, as well as in hospitals (Patterson, 1985). Rood, Chillary, and Collister (1985) have adapted Patterson's guidelines to the conditions found in military helicopters. The authors point out certain differences between helicopters and civil aircraft. The pace of life on a helicopter flight deck is much faster than in a civil airliner, and the noise spectrum is different. Rood and his colleagues recommend a double burst of an attenson followed by a voice warning, with repeats as appropriate. Each primary warning has its own attenson, made distinctive by pulse and burst parameters, with urgency controlled both by spectral and temporal characteristics. Spectral characteristics are matched to the particular aircraft, helmet, and the response characteristics of transducer in use (Rood et al., 1985).

To assist in tailoring warning signal parameters to specific aircraft, Lower and Wheeler (1985) have developed a desk-top computer program to predict masked thresholds for warning signals in a given noise environment. The program has been validated by comparing measured and predicted thresholds in recorded noise from Chinook, Sea King, and Lynx helicopters. The investigators found a high correlation between measured and predicted masked thresholds (Lower & Wheeler, 1985).

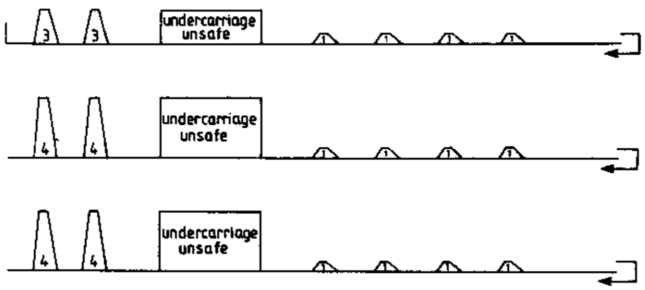

FIGURE 10. Time course of a complete auditory warning signal with voice message. (Patterson, 1982. Reprinted by permission.)

Coleman and his colleagues at the U.K.'s National Coal Board drew heavily on Patterson's work in developing guidelines for warning signals in industrial operations in general and coal production in particular (Coleman et al., 1984). They noted that Patterson's guidelines were designed for aircraft cockpits, but they could be effectively used in certain other environments such as control rooms. They also pointed out that Patterson's signals differed mainly in the temporal domain, whereas frequency and level characteristics could also be varied. In addition to Patterson's technique, Coleman et al. relied on ideas from Deatherage (1972) and Licklider (1961) in formulating the following Guidelines for the Production of Discriminable Sets of Signals (from Coleman et al., 1984, pp. 60–61):

1. Limit the number of signals to six at any one workplace.
2. Use no more than two signals when only one signal characteristic, such as pitch, is altered.
3. Ensure that at least three harmonically or pseudoharmonically related spectral components occur in the range 1–2 kHz for each signal.
4. Ensure that signals differ both in terms of their temporal patterns and their constituent perceptual units.
5. To manipulate temporal pattern, use modulation (AM or FM) at rates of 1–4 Hz, employing rest periods between bursts of sound as part of the temporal pattern.
6. Ensure that the modulation rate does not correspond with fluctuation rates in the environmental noise.
7. To manipulate within perceptual units, use different pitch and higher frequency modulation (AM or FM) at rates above 20 Hz. To manipulate pitch it is best to use complex signals comprising several harmonically related components. Such signals have a fixed perceived pitch regardless of the particular order of the harmonics (see Plomp, 1967). Masking some of the components will not alter the perceived pitch; therefore, signals made up of many harmonically related components can be more resistant to the effects of short-term noises in terms of maintaining both their audibility and perceived identity. In following this recommendation it should be remembered that the frequency of the fundamental present in the signal or implied by the harmonics should be below 1 kHz.

1.7 SUMMARY

1.7.1 Speech Variables

The proper assessment of speech communication conditions requires knowledge of the speech level. A number of different methods of measuring speech level are in use now, yielding differing results, although the relationships among these methods are fairly stable. People do not always talk at the same level. In live-voice situations, it should be kept in mind that people raise their voices about 5–6 dB for every 10-dB increase in background noise, and that vocal effort increases with distance and even with different forms of activity.

Normal speech is highly redundant, especially the special phraseologies often used in military situations. Because of conditions of noise and filtering, however, redundancy is significantly reduced. A variety of useful speech materials are available, and it is important to select appropriate materials to evaluate the particular noise conditions, communication system, and communication needs at hand.

We seldom listen to speech in ideal circumstances. Filtering characterizes communication systems, and noise masking is the most common source of speech interference. The upward spread of masking makes high levels of noise disproportionately disruptive. Combined distortions act synergistically to degrade communication.

1.7.2 Transmission Characteristics

Intelligibility of the speech signal is modified by distance, reverberation, and spatial location with respect to the noise source. Speech level is reduced by 6 dB per doubling of distance outdoors, but the reduction is less indoors because of reverberant build-up. Reverberation begins to degrade speech intelligibility at about 0.8 sec in quiet, and at less than 0.5 sec in noisy backgrounds. The effect is greater in small rooms than in large rooms. Separation in space of the speech and noise signals can result in improvements equivalent to a speech-to-noise ratio of 5 dB.

Binaural listening provides improvements of anywhere from 2.5 to 13 dB, depending mainly on noise and reverberation conditions. Telephone listening is difficult in noise because the filtering involved reduces speech redundancy and background noise reduces it further. Intelligibility can be improved by reducing side-tone feedback, through occluding or modifying the transmitter or by amplifying the signal. Current communication systems are frequently outmoded, causing strain and delays on the part of the listener, but there are many possibilities for improvement.

1.7.3 Talker and Listener Variables

Although individuals are capable of producing voice levels as high as 100–105 dB, they cannot sustain speaking levels above an asymptotic level of about 78 dB without considerable discomfort. Individuals who must habitually communicate in noise over a period of years are subject to voice disorders, such as hoarseness and vocal nodules. Talker articulation can greatly affect speech intelligibility. Studies have shown improvements of up to 18% from speaking clearly in quiet. Improvements also occur in noisy conditions, but appear to be somewhat less dramatic. Female voices are as intelligible as male voices in low and moderate noise levels, but may be slightly less intelligible in high noise levels.

Preferred listening levels under earphones are identified as sound pressure levels of 80–85 dB in quiet. With the introduction of noise, preferred levels are somewhat lower. Tolerable listening levels are lower for negative than they are for positive speech-to-noise ratios. Comfortable listening levels should be at a speech-to-noise ratio of at least 5 dB, and preferably above 10 dB. Non-native listeners have significantly more difficulty understanding degraded speech in their second language, even though they may be fluent speakers of that language. High levels of speech and noise can cause auditory fatigue (both central and peripheral, it appears), which reduces speech discrimination both simultaneously and subsequent to the high-level stimulation.

1.7.4 Prediction Methods

The Articulation Index (AI) is a popular and highly respected method of predicting speech intelligibility in noise. It has been modified and improved by the inclusion of corrections for such conditions as reverberation, spread of masking, peak clipping, changes in vocal effort, lipreading, and hearing impairment.

Speech Interference Level (SIL) is useful for predicting distances at which "just reliable" communication can occur. It has recently been modified to apply to indoor situations and numerous levels of vocal effort. However, its utility is limited because it cannot be used for people with hearing impairment or for other than face-to-face communication situations, and it uses only one level of intelligibility.

The Speech Transmission Index (STI) takes into account volume and reverberation time of the room, noise level, and distance between talker and listener, yielding a value similar to the AI. Research by the Netherlands group that developed the STI shows this method to be a good predictor of speech communication in a wide variety of conditions.

The sound level meter's A-weighting network can be a good predictor of speech interference with the advantage of being inexpensive and easy to use. Other interesting weighting networks have been proposed, but have not been incorporated into the standard sound level meter.

Although the above schemes use different measurement methods, the products can be related in a fairly predictable way. For example, 70% monosyllable intelligibility can be achieved at an AI of 0.45 or an STI of 0.55, which corresponds to a speech-to-noise ratio of about 1.5 dB.

1.7.5 Acceptability Criteria

There is general agreement that minimal or "just reliable" communication can take place at an AI of 0.3 to 0.45, but those who recommend these values give little information about the use of this level of communication. Although the literature is virtually silent on the specific types and amounts of communication needed for various operations, there are numerous recommendations for the range of background noise levels appropriate for certain activities and spaces. Examples include levels of 56–66 dB(A) for shops, garages, and power plant control rooms, down to 21–30 dB(A) for large auditoriums and concert halls.

The only references in the literature to the consequences of degraded speech tend to be anecdotal or subjective. However, it is obvious that normal patterns of communication can break down in emergencies, and the consequences of misunderstood instructions can be as serious as the destruction of expensive property, or even loss of life.

1.7.6 Detection of Warning Signals

Because a warning signal is detectable does not necessarily mean it will be effective. Ideally, a signal should be at least 15 dB but no more than 25 dB above its masked threshold. Temporal, spectral, and ergonomic aspects should emphasize attention demand, relevance, and appropriate level of priority, without being unduly aversive.

1.8 REFERENCES FOR CHAPTER 1

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Chapter 2

The Effects of Hearing Loss on the Perception of Speech and Warning Signals

Chapter I emphasized the importance of speech communication for the proper function of most jobs, as well as for the satisfactory conduct of social and personal relations. In addition to noise, loss of hearing degrades speech communication in these vital functions. The extent to which hearing impairment may degrade performance is the subject of the review and analysis contained in this section.

Noise and filtering, which are common in everyday communication situations, have the effect of reducing the natural redundancy in speech. When the listener is hearing impaired, redundancy is further reduced, to the point where the listener must strain to understand the messages communicated. Depending on the degree of hearing loss and the degradation of the speech signal, messages may be correctly perceived, partly or completely misunderstood, or missed entirely. The consequences of communication failures can range from minor annoyances to disasters.

Recently, some municipalities have shown an interest in establishing hearing sensitivity criteria for certain kinds of occupations, such as police officer, fire fighter, and transit operator, although these kinds of requirements are not very common. In the U.S. military, however, all three branches of the armed services incorporate hearing threshold level requirements into their criteria for induction, retention and appointment, and the performance of various jobs. Details of these requirements are presented in the appendix.

According to the National Institutes of Health (1990), approximately 28 million people in the United States have impaired hearing. Although there is little evidence on the number caused by noise, an estimated one million workers in the manufacturing industries have hearing threshold levels greater than an average of 25 dB at 1000, 2000, and 3000 Hz (OSHA, 1981), and many more have incurred hearing losses that are less severe. More than nine million Americans are employed in occupations in which the time-weighted average noise exposure level exceeds 85 dB(A) and are therefore at risk of developing some amount of hearing loss (EPA, 1981). Noise-induced hearing losses may result from recreational as well as occupational causes. These losses may be temporary, permanent, or combinations of the two. High-frequency hearing (in the 3000 to 6000 Hz range) is earliest and most severely affected by most noise exposure.[2]

A large portion of the hearing-impaired population will suffer from presbycusis, the loss of hearing that accompanies the aging process. The extent and severity of presbycusis naturally depends upon the age group examined, but also on audiometric frequency and gender. Like noise-induced hearing loss, high-frequency hearing is usually the earliest and most severely affected, with the progression toward the mid-frequencies occurring with increasing age. Average values of presbycusis are higher for men than for women.

Estimates of presbycusis in populations are also greatly affected by the amount of screening used in selecting the test population. An example of a highly screened European population is found in ISO 7029, the widely used international standard for hearing threshold level as a function of age and sex (ISO, 1984). These presbycusis data are also used in Annex A of ISO 1999, the international standard for estimating noise-induced hearing loss (ISO, 1990). In the selection of subjects for this data base, people with a history of noisy occupations or military service, as well as otological abnormalities, were excluded from the cohort. Annex B of the ISO standard contains a sample of an unscreened U.S. population, showing considerably more hearing loss in both male and female subjects. While Annex B is meant to portray age-related hearing threshold levels typical of an industrialized nation, it is difficult to know the relative contributions of occupational hearing loss, nonoccupational hearing loss (from recreational or military noise, for example), and "pure" presbycusis. There are some who would maintain that once the noise-induced component from every source is subtracted, there would be very little presbycusis left.

Noise and aging are probably the most common causes of hearing loss, but they are not the only ones, by any means. Those who need to communicate on the job are subject to the same sources of hearing impairment as the general population. These sources include impacted earwax, middle ear infections, and inner ear disorders caused by viruses, heredity, or ototoxic drugs. But noise-induced hearing loss and presbycusis, as well as other sensorineural impairments, will cause particular difficulties in the recognition of speech. Because consonant sounds tend to be high in frequency and low in sound energy, and because they contribute most of the intelligibility to speech, high-frequency hearing loss acts as a very effective filter to remove the intelligibility from speech. When added to the inherent distortion, which is present to some extent in most impaired auditory systems, even mild hearing impairments can place the listener at a disadvantage in certain situations.

2.1 EFFECTS OF HEARING LOSS ON SPEECH RECOGNITION

2.1.1 Filtering Versus Distortion

Certainly one of the most plausible explanations for the difficulties encountered by people with noise-induced hearing loss is that the hearing loss acts as a low-pass filter. This is even born out in the speech of some people who have experienced their hearing losses over a period of years, in that they tend to drop consonants from the ends of

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[2] For a more detailed discussion of the development of damage-risk criteria for hearing loss see Suter (1988).

words. Because of this filter effect, researchers such as Kryter (1970), Braida et al. (1979), and Skinner and Miller (1983) have proposed corrections for hearing impairment to the Articulation Index (AI).

Levitt (1982) has summarized the filter effect succinctly. For the mildly hearing-impaired individual, most of the weaker consonants, such as sibilants and voiceless stops, will be barely audible or inaudible. This effect will be greater when these phonemes occur in the final position or in blends, where their intensity will be lower. The person with more severely impaired hearing will miss the identifying cues for all voiceless sounds and also many of the weaker voiced consonants, such as voiced stops in the final position.

Although there is still some controversy over the issue of filter versus distortion, there is a mounting body of evidence indicating that filtering is not the only problem for hearing-impaired listeners. Plomp (1978) divides hearing losses into Class A, attenuation, and Class D, which is added distortion. Class D listeners are those who say, "I can hear you talking, but I can't understand what you are saying." Class A individuals have difficulty at low speech and noise levels, but their hearing approaches that of normal listeners at high speech levels, even when the speech is accompanied by high levels of noise. Class D people have minor difficulties in low noise levels but substantial problems in high levels of noise and speech. This difficulty is manifest in the speech recognition function that plateaus or "rolls over" at levels considerably lower than 100% with increasingly higher listening levels. Plomp believes that most actual hearing losses are combinations of Class A and Class D, and as a rule of thumb he estimates that for every 3-dB increase in the speech reception threshold (SRT) for sentences, the distortion or "D" component increases by 1 dB. (One can assume that purely conductive losses would be categorized as Class A only.)

This controversy has been the subject of several investigations over recent years. The earlier studies found few differences between the abilities of subjects with actual hearing losses and those who listened through low-pass filters (Sher & Owens, 1974; Bilger & Wang, 1976; Wang et al., 1978). An exception is an experiment by Chung and Mack (1979) that introduced low-pass filtering with a cutoff at 2000 Hz in an attempt to make the test conditions physically comparable for normal-hearing subjects and those with high-frequency hearing losses. Each subject was tested at three speech levels (65, 75, and 85 dB) with three different speech-to-noise ratios (+5, +12, and +19 dB). Although the effect was "not as overwhelming" as in some other investigations, the hearing-impaired listeners performed significantly more poorly than their normal-hearing counterparts, especially at higher speech levels and less favorable speech-to-noise ratios.

Walden et al. (1981) used an innovative approach to test the filter versus distortion issue on 14 subjects with unilateral hearing impairments. Using these subjects as their own controls, the investigators compared the consonant recognition ability of the impaired ear to that of the normal ear, listening through a filter shaped to the configuration of the impaired ear. Rather than using the audiometric configuration at threshold, Walden and his colleagues used a loudness balance procedure to shape the audiometric configuration at a normal listening level for speech. Although phoneme recognition analysis showed similar error patterns between the two ears, there was a mean difference between ears of 20.8% in the number of errors. The authors caution that generalization may be unwarranted because of the limited number of subjects, but they maintain that the results "do not support the often-made assumption that test results for normal-hearing subjects listening to filtered speech stimuli can be generalized to a hearing-impaired population" (Walden et al., 1981, p. 42).

2.1.2 Masking

Fabry and Van Tasell (1986) used masking as well as filtering to investigate the question of whether attenuation is the only disadvantage for listeners with hearing impairment. As in the experiment described above by Walden et al. (1981), their subjects (6) had unilateral, cochlear impairments. Some subjects showed better scores in the masked and filtered simulations than in the impaired ears, and other subjects showed the reverse. There were large differences among individual subjects and among listening modes in the same subject. The investigators found that masking and filtering simulated the error patterns in about half their subjects. They conclude that for some people the major effect of sensorineural hearing loss is attenuation, but (obviously) not for all. One could also conclude from their study that the degree to which the distortion effect manifests is highly variable among individuals.

Humes et al. (1987) point out that masking may be a better simulator of cochlear impairment than simple filtering because there is evidence that the threshold elevations resulting from masking are predominantly cochlear, and that in addition, noise-masked listeners with normal hearing demonstrate loudness recruitment (as do people with cochlear impairments). The investigators chose four subjects with bilaterally symmetrical sensorineural hearing impairments, each of whom was matched with three normal-hearing subjects whose noise-masked thresholds were nearly identical to those of the hearing-impaired subject. Recognition of nonsense syllables at three listening levels showed that under most conditions, the hearing-impaired subjects performed as well as or better than the noise-masked subjects. Humes and his colleagues reasoned that if some deficit other than cochlear threshold elevation and loudness recruitment had been present (some additional "D" component), the hearing-impaired listeners would have performed more poorly than the noise-masked normal listeners. As it was, they concluded that their four listeners did not have these processing deficits, or if they did, they did not affect overall speech-recognition performance. Although Humes et al. claim that their four subjects "*never* performed worse than the noise-masked normal hearers" (p. 772), their data show that two of the four often performed more poorly than their normal-hearing counterparts at the highest speech levels.

These experiments do not support the existence of an additional distortion component, but they do show the complexity of the issue. Other types of experiments employing masking do show differences between the performance of listeners with normal hearing and those with sensorineural hearing loss.

Noise masking is a common occurrence in "everyday" listening conditions. Plomp (1978) estimates that 50% of speech communication takes place in A-weighted ambient noise levels of 50 dB or above. Many occupational environments are considerably noisier, and military conditions would be no exception.

Presumably because of the distortion component, most hearing-impaired listeners appear to need more favorable speech-to-noise ratios than do normally hearing listeners. According to Plomp (1978), a person with a purely Class D hearing impairment needs a speech-to-noise ratio that is 10 dB more favorable than a normal listener would require. Assuming that most hearing losses are combinations of Class A and Class D, one would expect an increment somewhat smaller than 10 dB in real life. Smoorenburg (1982) measured SRT for sentences in 7 normal-hearing subjects and 22 subjects with noise-induced hearing loss in quiet and at A-weighted noise levels of 25, 40, 55, and 70 dB. For 50% correct sentences, the median speech-to-noise ratio was −5.5 dB for subjects with normal hearing and −1.8 dB for hearing-impaired subjects. Thus, the hearing-impaired subjects needed a speech-to-noise ratio that was 3.7 dB more favorable than the normal-hearing listeners. Although this may not appear to be a significant increment, it represents a difference in intelligibility score of 60% (Smoorenburg, 1982).

As the level of a noise increases, its masking efficiency also increases because of the phenomenon known as the upward spread of masking. According to Bess (1983), the popular notion that people with hearing impairment are disproportionately affected by the upward spread of masking is an exaggeration. He claims that the actual effect is no different from the effect on normal-hearing listeners when the masking stimulus is presented at the same sound pressure level for all subjects (presumably instead of at the same sensation level). Martin and Pickett (1970) did find higher absolute masked thresholds for hearing-impaired than for normal-hearing listeners at high levels (e.g., 107 dB), although the actual threshold shift was often less. They found considerable variability among subjects, and the amounts of upward spread of masking were not strongly related to the degree of hearing loss. More recently, Picard and Couture-Metz (1985) used subjects with normal mid-frequency hearing and losses in the high frequencies. In response to a masking noise centered at 1000 Hz, the hearing-impaired listeners showed greater spread-of-masking than normal-hearing controls at masking levels of 80 dB and above. This effect occurred despite hearing within normal limits at the frequency of the masker.

Gagne (1988) assessed upward spread of masking in people with hearing impairment by plotting the level of masked thresholds as a function of masker level, using only masked thresholds that exceeded a subject's hearing threshold level in quiet. He defined "excess" masking as the difference between actual and calculated thresholds, the calculations being the power sum of expected values from normal-hearing listeners plus the hearing-impaired subject's threshold levels in quiet. The results showed considerable amounts of excess masking, which varied according to degree of hearing loss and audiometric configuration. To assess the validity of his method for determining excess masking, Gagne tested normal-hearing listeners with simulated hearing losses, and excess masking was not evident. Gagne then applied his method to analyze the data of several other spread-of-masking investigations, and found results to be quite consistent with his own. He concluded that the inconsistencies previously reported were due to differences in experimental paradigms and methods of analysis, and that taken as a whole, the data do show greater than normal spread of masking in hearing-impaired subjects, with consequent reductions in frequency selectivity.

2.1.3 Distortion

Clinicians have known for many years that some of their patients exhibit significantly greater difficulty understanding speech than others, even though their audiometric configurations may be identical. Likewise, adjusting hearing aid output to mirror the configuration of an audiogram usually produces unsatisfactory results. Many, if not most, individuals with sensorineural hearing impairments are affected by some sort of cochlear dysfunction that renders them somewhat less able to use their residual hearing than one would predict from filtering exercises. Distortions cited in the literature include reduced sensitivity to intensity change; reduced frequency selectivity; loudness distortion; poorer temporal processing ability; broader critical bands and poorer ability to extract signals from noise; greater spread of masking; nonlinear distortion components; and reduced linear range of the auditory system (Levitt, 1982). Levitt cautions that most of the studies "show correlational rather than causal relationships" and that speech recognition is usually correlated with only one other variable, whereas this correlation could be the result of a mutual correlation with a third, unspecified variable (Levitt, 1982, p. 38). He cites certain multivariate studies showing that once the degree of hearing loss is extracted, the correlation with other psychoacoustic variables is reduced, but not eliminated. He emphasizes that the addition of noise greatly increases the effects of auditory distortion, beyond what one would predict from the proportion of the speech spectrum available to the listener.

The growing body of research in otoacoustic emissions (OAEs) adds to the information on cochlear distortions. Whereas many of the normal ear's functions are linear, it appears that many others are not. In a comprehensive review of the subject, Probst et al. (1991) point out that the response of the OAE reflects nonlinear processes in that the amplitude of the emission is not directly proportional to that of the incoming stimulus and the OAE consists of frequencies that are not present in the stimulus. OAEs, however, are reduced or absent in individuals whose hearing losses exceed 25 to 30 dB (at the impaired frequencies). Probst and his coauthors state that more than 30 years ago, Gold (1948) hypothesized that the cochlea's capacity for sharp frequency selectivity resulted from a feedback system, a mechanical-to-electrical transduction process coupled to an electrical-to-mechanical transduction process. But this theory was not taken seriously until Kemp (1978) demonstrated OAEs using specialized methods and equipment (Probst et al., 1991). Now it appears that the same mechanism may be involved in both frequency selectivity and the OAE.

2.1.3.1 *Frequency distortion.* There is considerable evidence that difficulties experienced by listeners with hearing impairment are related to decrements in the ear's ability to separate the frequency components of a complex sound, referred to as frequency selectivity or resolution. Tyler (1986) states that degraded frequency resolution may be the most important consequence of cochlear impairment.

As suggested earlier, hearing-impaired listeners are often more affected by masking than their normal-hearing counterparts. In his extensive review of frequency resolution in listeners with impaired hearing, Tyler (1986) points out that frequency resolution is accomplished by an auditory filter centered on the signal frequency. In the listener with normal hearing, this filter passes only a relatively narrow band of frequencies close to the signal. People with sensorineural hearing loss, however, often have widened auditory filters, which allow more masking. Many listeners with hearing impairment show elevations of masked thresholds, and there is considerable intersubject variability, in that listeners with similar hearing threshold levels can have very different masked thresholds (Tyler, 1986).

Buus and Florentine (1989) found that impaired ears show more effects from masking than normal ears with simulated impairments. Also, as mentioned earlier, people with hearing impairment are more severely affected by upward spread of masking, but pronounced downward spread can also occur (Tyler, 1986).

Additional evidence of degraded frequency selectivity in hearing-impaired listeners comes from the study of neural and psychophysical tuning curves. A neural tuning curve can be described as a set of frequency-intensity combinations that cause a particular nerve's firing rate to exceed by a fixed amount the rate at which it discharges spontaneously (Salvi et al., 1982). Tuning curves for high-frequency nerve fibers usually have a sensitive tip (i.e., a low threshold) and a higher-threshold, broadly tuned "tail," meaning that the nerve will respond to frequencies other than its characteristic (tip) frequency, but greater intensity is required for frequencies that are progressively lower than the characteristic frequency. Noise-exposed animals show widened neural tuning curves, as do human subjects with a variety of hearing losses tested with psychoacoustic procedures.

The psychophysical tuning curve (PTC), in many ways the analogue of the neural tuning curve, can be assessed in human subjects using a low-level fixed signal and a masking signal that varies with frequency. The shape of the PTC is determined by plotting at several frequencies the level of the masking signal that just masks the fixed tone. Tyler (1986) reports on numerous studies showing that hearing-impaired subjects have sharply tuned PTCs in frequency regions with normal hearing threshold levels and abnormally widened PTCs in regions with elevated hearing threshold levels. Some, with hearing threshold levels greater than 40 dB, display W-shaped tuning curves. Again, there is a great deal of variability among subjects. For example, Buus and Florentine (1989) found one subject whose PTC was nearly identical to those of three normal-hearing listeners simulating his loss, whereas another subject showed a much shallower PTC in her impaired ear than in her other (normal) ear, which had been masked to simulate her impaired ear.

Tyler's review also covers experiments that have been conducted using spectrally complex maskers, such as noise on increasing bandwidth, "comb-filtered" noise, "notched" noise, and two-tone masking, that have demonstrated frequency resolution decrements in hearing-impaired listeners (Tyler, 1986).

Florentine et al. (1980) tested four different measures of frequency selectivity on individuals with various types and degrees of hearing impairment. The authors define frequency selectivity as the ability of the auditory system to separate the frequency components of a complex sound. The measures were narrow-band masking, psychoacoustic tuning curves, two-tone masking, and loudness summation. All four measures showed reduced frequency selectivity on the part of subjects with cochlear impairments, with psychoacoustic tuning curves and narrow-band masking proving to be the most efficient tests. Florentine and her colleagues state that although they could not be sure that their data accurately reflect the *amount* of change in the frequency-selectivity mechanism, they "have no doubt that frequency selectivity is radically altered in cochlear impairment" (p. 666).

The practical significance of abnormalities in frequency resolution are that cochlear impairments increase the difficulties in understanding speech beyond what would be experienced simply by attenuation. Rosen and Fourcin (1986) maintain that even those with mild-to-moderate hearing losses will have some amount of degradation of frequency resolution that results in some parts of the speech signal masking others. But the effects are especially true of listening in noisy environments. The same authors cite several studies of frequency resolution and speech recognition in quiet that show no significant correlation, although those in noise do. Broadening the auditory filters renders the hearing-impaired person more susceptible to noise. It decreases the signal-to-noise ratio in frequency areas that would remain unaffected in the normal-hearing listeners, and can even interfere with temporal decisions, such as the perception of a short silence indicating a consonantal closure (Rosen & Fourcin, 1986).

2.1.3.2 *Intensity distortion.* Although it has not been the subject of as much recent research as the field of frequency distortion, intensity distortion can also lead to difficulties in speech communication. Perhaps the most widely recognized intensity problem is the phenomenon known as recruitment, which is the abnormal increase in the growth of loudness in the ear with cochlear pathology. The recruiting ear perceives loudness over a limited dynamic range. It may or may not "catch up" to the normal ear at high sound levels, or it may "over recruit" meaning that loudness becomes greater than normal at high levels. People with hearing impairment with recruitment may pose a special problem for communication systems, in which low-level stimuli need to be amplified considerably but high-level stimuli need to be compressed or clipped before reaching an individual's tolerance level.

The recruitment phenomenon frequently does not "improve" intensity discrimination as one might expect. Listeners with sensorineural hearing losses do not always show abnormally small difference limens for intensity. For example, Fastl and Schorn (1981) (cited in Moore, 1989) found that the intensity difference limen in subjects with retrocochlear hearing losses may be much larger than normal. Scharf and Florentine (1982) point out that the just-noticeable difference for intensity is often smaller in hearing-impaired than in normal-hearing listeners when presented at the same sensation level, but not when presented at the same sound pressure level. A study reported by Florentine et al. (1979a) showed poorer intensity discrimination in the impaired ear than in the normal ear of the same listener when the stimulus was presented at equal sound pressure levels, whereas performance at the same sensation level was comparable for the two ears. Interestingly, the same investigators also found that intensity resolution in 2 of the subjects with cochlear impairments was impaired even at frequencies where hearing threshold levels were within the normal range.

2.1.3.3 *Distortions in temporal processing.* Abnormalities in temporal processing also appear to characterize cochlear impairments. Because much of the information in speech is carried in the transient rather than in the stable parts of the speech signal (Moore, 1989), decrements in temporal processing are likely to cause difficulties in speech recognition.

Early research (cited by Moore, 1989) has shown that both hearing threshold level and the loudness of sounds depend on duration. For durations less than 200 msec, the intensity necessary for detection increases as duration decreases. The slope of this relationship is approximately −3 dB per doubling of duration, and hence the term temporal integration. According to Moore (1989) and Stephens (1976), people with sensorineural hearing impairments tend to have shallower temporal integration functions than those with normal hearing. Abnormalities in temporal integration may impair a person's ability to discriminate suprathreshold stimuli as well.

Florentine et al. (1988) report numerous studies showing decreased temporal integration in listeners with cochlear impairments. The authors hypothesize that these decrements could be caused by "spectral splatter" to frequencies where hearing threshold levels were better. The results of their experiment showed that normal-hearing listeners with hearing losses simulated by masking achieved approximately the same amount of temporal integration as those without masking. The subjects with cochlear impairments, however, showed reduced temporal integration, indicating that the effects were not caused by spectral splatter but by actual reduction in temporal integration capabilities.

Temporal resolution, which is the ability to detect changes in the temporal characteristics of sounds, also appears to be affected in hearing-impaired listeners. Zwicker and Schorn (1982) found significant differences in temporal resolution between subjects with several types of hearing impairments and normal hearing subjects whose thresholds had been elevated by masking to simulate hearing losses. The performance of hearing-impaired subjects became increasingly affected as background noise levels were increased.

In another temporal resolution experiment, Florentine and Buus (1984) tested the abilities of individuals to detect gaps, or brief pauses in continuous noise. Six normal-hearing subjects, 7 with cochlear hearing impairments and 8 with hearing losses simulated by masking, listened for gaps in a white noise stimulus. The investigators found that some of the differences between hearing-impaired and normal-hearing listeners could be explained by audiometric configuration, an indication that high-frequency hearing is important for gap detection. Some of the hearing-impaired subjects performed similarly to those with simulated hearing losses. The functions of other hearing-impaired subjects, however, were enlarged, and the authors concluded that these subjects had actual difficulties with temporal resolution.

Tyler et al. (1982) tested several measures of temporal processing as well as frequency resolution tasks on normal-hearing and hearing-impaired listeners. Most hearing-impaired subjects showed poorer results than the normal-hearing listeners on all tasks, regardless of whether the two groups were compared at similar sound pressure levels or sensation levels. Two of the temporal processing effects, increased temporal difference limen (just-noticeable differences in stimulus duration) and longer gap detection thresholds, correlated significantly with impaired speech recognition ability. These effects persisted after adjustments had been made for loss of attenuation. The authors conclude that these temporal processing disabilities "may represent the important underlying processes that contribute to the poor speech perception in the hearing impaired" (p. 750).

2.1.2 Binaural Processing and Localization

The importance of binaural hearing in localizing sound has been well established, both in normal-hearing and hearing-impaired listeners (see Blauert, 1983; Durlach et al., 1981; Durlach & Colburn, 1978; and Hausler et al., 1983, all as cited in Colburn et al., 1987). For example, Perrott et al. (1987) found that subjects who were rendered monaural by an earplug in one ear displayed significant impairments in the ability to localize sound, although this disability was mitigated when they listened to a train of pulses rather than a single pulse. In another study, this time using truly monaural listeners, Hausler et al. (1983) (as cited in Colburn et al., 1987) used the minimum audible angle (MMA) to determine localization performance in monaural listeners. The results showed that localization for tones was more successful in front and back than on the sides, and confirmed the finding that high-frequency spectral information is especially useful when localization is performed monaurally.

In a review of the subject of binaural directional hearing, Colburn and his coauthors cite research in addition to Hausler's indicating various disadvantages on the part of listeners with hearing impairment (Colburn et al., 1987). They mention research on normal-hearing listeners showing that an intensity imbalance can impair discrimination of interaural time, discrimination of interaural intensity, and binaural masked detection. They theorize that some of the abnormal findings in pitch perception and temporal resolution may actually be due to the intensity imbalances characteristic of individuals with asymmetrical hearing losses.

Colburn et al. (1987) proceed to describe the binaural performance of subjects with various kinds of hearing impairment: Subjects with conductive hearing losses greater than about 35 dB appear to have considerable difficulty in most binaural tasks, and unilateral losses are more disruptive than bilateral ones. Subjects with cochlear impairments of approximately the same magnitude perform somewhat better, although they show some decrements for discriminations of interaural time, intensity, and correlation in narrow-band as opposed to wide-band noise. Retrocochlear impairments are characterized by large variations in performance among subjects, ranging from normal performance (Hausler et al., 1983) to no binaural abilities at all (Florentine, et al., 1979b).

2.2 HEARING HANDICAP

Most professionals who work with people with hearing impairment would agree that small amounts of hearing loss cause no handicap, and are often not even noticeable to the affected individual. The question is, then, how much hearing impairment can a person acquire before he or she can no longer function adequately in social or occupational settings?

2.2.1 Definitions

Three terms, *impairment, handicap,* and *disability,* are often used interchangeably, but they refer to very different concepts. To confuse the issue further, they are defined differently by different authorities.

In 1965 the American Academy of Ophthalmology and Otolaryngology (AAOO) made the following distinctions (Davis, 1965):

- Impairment: a deviation or change for the worse in either structure or function, usually outside the range of normal.
- Handicap: the disadvantage imposed by an impairment sufficient to affect one's personal efficiency in the activities of daily living.
- Disability: the actual or presumed inability to remain employed at full wages.

Probably the most logical set of definitions have been put forward by the World Health Organization (WHO) (1980), which defines these terms in the context of all health experiences:

- Impairment: any loss or abnormality of psychological, physiological, or anatomical structure or function.
- Disability: any restriction or lack (resulting from an impairment) of ability to perform an activity in the manner or within the range considered normal for a human being.
- Handicap: a disadvantage for a given individual, resulting from an impairment or a disability, that limits or prevents the fulfillment of a role that is normal (depending on age, sex, and social and cultural factors) for that individual.

The British Association of Otolaryngologists and the British Society of Audiology (BAOL/BSA, 1983) have adapted these terms to the audiological context, such that *impairment* is defined similarly to the way it is in the United States, but *handicap* and *disability* are reversed:

- Disability: any lack or restriction (resulting from an impairment) of ability to perceive everyday sounds, either in quiet or a noisy background. It is usually given in a scale of percentages for compensation purposes.
- Handicap: the disadvantage for a given individual resulting from impairment or disability that restricts activities that would be expected for that individual.

The U.S. Department of Labor's Occupational Safety and Health Administration (OSHA, 1981) adds the concept of "material impairment of hearing," which is somewhere between the AAOO's concepts of impairment and handicap. It is the protection goal for the setting of standards to prevent occupational hearing impairment. OSHA defines it as the point or "fence" beyond which an individual cannot function as well as a normal-hearing person.

The AAOO's use of *handicap* and its attendant meaning is reasonably well understood in the United States, despite the fact that most state workers' compensation laws use the word *impairment* with the AAOO's formula for handicap. Although the British definition is probably more accurate, because the AAOO's use of the word *handicap* is more familiar in the United States, it will be used for purposes of this section. The U.S. medical community and those who draft workers compensation laws would do well to consider the WHO and British usage in any further deliberations on this issue.

2.2.2 Audiometric Thresholds Defining Hearing Handicap

The point of beginning handicap has been the subject of much discussion and investigation over recent decades. Early experiments focused on the relationship between speech recognition and used the term *hearing loss for speech* since the distinctions between impairment, handicap, and disability had not yet been made. The first well-known method for assessing hearing loss for speech was developed by Fletcher (1929). Fletcher's time-honored "Point Eight Rule" divided the entire audible range from 0 to 120 dB (ASA) for the averaged frequencies 500, 1000, and 2000 Hz into percentage of loss with a slope of 0.8% per decibel. For many years, physicians used Fletcher's rule to calculate compensation for hearing loss, even though it was not meant for that purpose. Later, the AMA adopted the Fowler-Sabine method in 1947. By this method, average hearing threshold level was calculated for the audiometric frequencies 500, 1000, 2000, and 4000 Hz, which were given the weightings 15%, 30%, 40%, and 15%, respectively. The "low fence" or the point of beginning handicap was identified as an average hearing threshold level of 10 dB (ASA, or 20 dB ANSI) (AMA, 1947).

According to Davis (1973), the new formula was too complex, and otologists refused to use it. Accordingly, the AAOO (1959) developed a simple method, which many state statutes still employ today. The new method used the simple average at 500, 1000, and 2000 Hz with a low fence at 15 dB (ASA, or 25 dB ANSI), a high fence (or point of total handicap) at 82 dB, and a growth of handicap of 1½% for each decibel between these points. The AAOO believed that hearing impairment should be evaluated in terms of the ability to hear "everyday speech" and that the ability to hear sentences and repeat them correctly in a quiet environment was satisfactory evidence of good hearing for everyday speech (AAOO, 1959). The AAOO determined that the average hearing level of 16 dB (ASA, or 26 dB ANSI) at 500, 1000, and 2000 Hz was the point at which people begin to have difficulty hearing sentences in quiet and seek medical help for their hearing problems. This determination was based on clinical evidence (Davis, 1973).

Over the following two decades, many studies were conducted to discover the audiometric frequencies that best predicted hearing handicap and the average hearing threshold level at the selected frequencies that marked the point of beginning handicap. Many, although not all, of the earlier studies, which were conducted in quiet backgrounds, pointed toward the importance of mid-frequency hearing for understanding speech (for example, Harris et al., 1956; Quiggle et al., 1957; and Quist-Hanssen & Steen, 1960). Most later investigations used various types and amounts of noise backgrounds, presumably because noise is characteristic of many everyday listening conditions. Most studies of word recognition in noisy backgrounds have shown the importance of good hearing above 1000 Hz. The same is true with speech distorted by speeding (Harris et al., 1960) and reverberation (Robinson, 1984). Table 4 lists many prominent speech recognition/audiometric frequency studies conducted over the past 30 years, showing the audiometric frequencies identified as being most important for understanding speech under various conditions of noise and distortion.

Because of the importance of high-frequency hearing for understanding speech in less than optimal conditions, the American Academy of Otolaryngology–Head and Neck Surgery (AAO-HNS)[3] decided to include 3000 Hz in the definition of beginning hearing handicap. The low fence remained at 25 dB (AAO-HNS, 1979). Many states have changed their workers' compensation statutes accordingly.

Other formulas of interest include the one recommended by the National Institute for Occupational Safety and Health (NIOSH, 1972) and later adopted by OSHA (1981) for purposes of preventive regulation. It identifies material impairment of hearing as an average hearing level of 25 dB or greater at 1000, 2000, and 3000 Hz. The rationale for the inclusion of 3000 Hz and the exclusion of 500 Hz is based on many of the studies listed in Table 4.

The British Association of Otolaryngologists and the British Society of Audiologists have recommended a low fence of 20 dB for the averaged frequencies 1000, 2000, and 4000 Hz, based on studies conducted in the UK, USA, and the Netherlands (BAOL/BSA, 1983).

The exact level of the low fence (or point of beginning handicap) has been the subject of much—and sometimes heated—debate. If the fence is set too high, a series of adverse social consequences will result. People with handicapping hearing loss will be ineligible for compensation. Workers in noisy environments will be denied regulatory protection. Soldiers, aviators, and other workers will be assigned to jobs in which they are unable to communicate adequately. If the fence is set too low, the opposite set of consequences will prevail. People will be compensated although their losses result either entirely or in part from presbycusis. Regulations will be unnecessarily stringent and expensive. Soldiers, aviators, and others will be disqualified from jobs in which they could have performed satisfactorily.

More recent investigations of the low-fence issue have attempted to pinpoint the hearing threshold level at which people with mild losses are no longer capable of understanding speech the way normal-hearing listeners do. On the basis of her data and those of Acton (1970), Suter estimated that the point of beginning handicap occurs at an average hearing threshold of 19 dB at 1000, 2000, and 3000 Hz (Suter, 1985). This point translates to approximately 9 dB at 500, 1000, and 2000 Hz, and 22 dB at 1000, 2000, and 4000 Hz, because most people with mild sensorineural impairments have audiometric profiles that slope toward the high frequencies. She observes, however, that the selection of a fence depends upon the definition of hearing handicap and the conditions under which handicap is assessed. As the data in Table 4 indicate, good hearing in the high frequencies becomes increasingly important as listening conditions become increasingly degraded.

Smoorenburg (1982, 1986) has also studied the question of the low fence. He defines the "onset of handicap" as the amount of hearing loss at the point that an individual first begins to notice a handicap in everyday (meaning some-

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[3] By 1979, the AAOO had split into two groups, the ophthalmology group on the one hand, and the otolaryngology/head and neck surgery group on the other.

TABLE 4. Studies showing the relationship of audiometric frequency to word recognition ability in individuals with hearing impairment.

Source	*Speech material*	*Environment*	*Frequencies most important for speech recognition*	*Comments*
Harris, Haines, and Myers, 1956	Harvard PB monosyllables (50% correct)	Quiet	av. 500, 1000, 2000 Hz	
Mullins and Bangs, 1957	Harvard PB monosyllables	Quiet	2000, 3000 Hz	
Quiggle, Glorig, Delk, and Summerfield, 1957	Spondees	Quiet	av. 500, 1000, 2000 Hz	
Quist-Hanssen and Steen, 1960	Norwegian monosyllables, disyllables, digits, and "context" speech	Quiet	av. 500, 1000, 2000 Hz	
Kryter, Williams, and Green, 1962	Harvard PB monosyllables and sentences	Quiet, noise, and low-pass filtering	2000, 3000, 4000 Hz	
Ross, Huntington, Newby, and Dixon, 1965	CID W-22 PB monosyllables	Quiet and noise	2000, 4000 Hz	Speech materials presented at 40 dB above SRT.
Acton, 1970	Fry's PB monosyllables	Quiet (S/N + 20)[1] and pink noise	2000 Hz	Subjects with mild high-frequency losses (above 2kHz) performed better than normal-hearing controls.
Elkins, 1971	MRT	Quiet and noise	2000, 3000, 4000 Hz in quiet, but no significant correlations in noise	Speech materials presented at 40 dB above SRT.
Lindeman, 1971	Dutch monosyllables	"Cocktail party" noise	2000 Hz	
Aniansson, 1973	Swedish PB monosyllables	9 different "everyday milieu" (traffic noise, competing speech and mild reverberation)	3000 and 4000 Hz just as important as 500 and 1000 Hz	
Kuzniarz, 1973	Polish monosyllables and sentences	Quiet, white and low-frequency noise	500, 1000, 2000 Hz in quiet, and 3000, 4000 Hz in noise	Recommended av. 1000, 2000, 4000 Hz to Polish Ministry of Health.
Suter, 1978	MRT and CID sentences	Quiet and speech babble noise (plus mild reverberation)	av. 1000, 2000, 4000 Hz in quiet; av. 2000, 3000, 4000 Hz in noise	
Smoorenburg, 1982	SRT for Dutch sentences	Quiet and four levels of speech-shaped noise	500 Hz in quiet, 2000–3000 Hz in noise	Pilot study—only 22 hearing-impaired subjects.
Robinson, 1984	1. Simulated social gathering: names, addresses and phone numbers	1. Speech babble, jazz music		Also included self-assessment questionnaires and tests of frequency and temporal processing.
	2. P.A. announcement in railway station	2. Railway station noise (plus reverberation)	av. 3000, 4000, 6000 Hz	
	3. Telephone listening	3. Noise at 2-dB S/N[1]		
	4. Sound field speech audiometry-CVC words	4. Speech babble at 2-dB S/N[1] (plus mild reverberation)	av. 1000, 2000, 3000 Hz	
Smoorenburg, 1986	SRT for Dutch sentences	Quiet and four levels of speech-shaped noise	250–1000 Hz in quiet, 2000, 4000 Hz in noise	200 hearing-impaired subjects. Frequencies above 1000 Hz show better correlation with speech recognition even in noise levels as low as 35 dB (A).

[1] S/N = speech-to-noise ratio.

what noisy) situations (Smoorenburg, 1986). Because hearing sensitivity at 2000 and 4000 Hz correlates so well with speech recognition in noise, Smoorenburg (1986) defines the "target SRT" as that point at which SRT begins to turn significantly upward as a function of average hearing level at 2000 and 4000 Hz. On the basis of data from 400 ears, he identifies this point as a mean SRT of −4.6 dB, which corresponds to an average hearing level of 10 dB at 2000 and 4000 Hz (a level that would be considered well within the range of normal hearing). Smoorenburg then identifies the level at which the SRT increases significantly at the 0.05 level of confidence, which is an SRT of −2.8 dB, corresponding to an average hearing threshold level of 24 dB at 2000 and 4000 Hz, or 15 dB at 1000, 2000, and 3000 Hz. SRT increases significantly at the 0.01 level of confidence at −2.0 dB, which corresponds to an average hearing threshold level of 32 dB at 2000 and 4000 Hz, and 22 dB at 1000, 2000, and 3000 Hz. Smoorenburg believes this (the 0.01 level) is an unacceptable hearing handicap.

In one of the most extensive investigations of this issue, Robinson et al. (1984) tested 20 normal-hearing and 24 hearing-impaired individuals in a variety of listening tasks, which included a simulated social gathering, public address announcements recorded in the Waterloo railway station, and a telephone listening situation in which speech and noise were mixed, all at a speech-to-noise ratio of 2 dB. They also administered CVC monosyllables in the sound field at several levels of speech and noise. The results showed large differences between the normal-hearing and hearing-impaired groups, but there were also large differences within groups and even within the same subject's responses across tests. Average hearing threshold level at 3000, 4000, and 6000 Hz correlated most highly with performance on the three simulations, and the average at 1000, 2000, and 3000 Hz correlated best with the speech audiometric tests.

Robinson and his colleagues concluded that they could not identify the threshold of disability (what we call handicap) on the basis of a discontinuity in the performance curve because this point is entirely dependent upon the difficulty of the test. "There are as many potential 'disabilities' as there are activities" (Robinson et al., 1984, p. 103). They decided that the function of the low fence is not to distinguish between circumstances but between people. They found that the 2nd percentile of performance by normal subjects (on the poor performance end of the scale) corresponded to hearing threshold levels at 1000, 2000, and 3000 Hz in the impaired group ranging from 27 to 34 dB for all of the tests. Because the performance of individuals with hearing threshold levels in this range was less dependent on particular tasks, they chose an average hearing level of 30 dB at 1000, 2000, and 3000 Hz as the threshold of disability.

Robinson and his colleagues make a very important point when they observe that the onset of handicap ("disability," in their words) varies according to task, so that the selection of any one set of conditions for the definition of beginning handicap is necessarily arbitrary. However, their selection of the 2% performance level of normal listeners is also somewhat arbitrary. It is based on a limited total number of subjects (20 normal-hearing and 24 hearing-impaired), and only one speech-to-noise ratio (2 dB). Only 5 subjects had hearing impairments as great as the 30 dB hearing threshold level at 1000, 2000, and 3000 Hz. The shape and smoothing of the curve might have produced different results had there been more subjects.

In the final analysis, it appears that the selection of the fence has been a matter of judgment, based on ground rules developed by the individual or organization involved. Whether it is the point at which the SRT increases at the 5% or 1% level of significance, or the 2% level of normal performance, or an estimated difference between groups performing normally or subnormally on speech recognition tasks, a judgment is necessary. Fortunately, these recent experiments have narrowed the range of beginning handicap to between about 15 and 30 dB at 1000, 2000, and 3000 Hz. The only way to narrow it further would be to take careful account of the listening conditions in the specific jobs or life conditions for which the assessment of handicap is needed. One must also remember that this 15–30 dB range applies to the recognition of everyday speech. Special circumstances, such as sentry duty in quiet areas, may very well require more sensitive hearing if the listener needs to detect faint or high-frequency sounds.

2.3 PREDICTING COMMUNICATION AS A FUNCTION OF HEARING LOSS

Some interesting schemes for predicting speech communication and communication losses have been developed by Kryter (1970, 1973, 1984). For one scheme he borrowed a graph from Stevens and Davis (1938, reprinted 1983). Figure 11, from Stevens and Davis, shows an estimate of the total number of distinguishable tones in the auditory area. These estimates were made by holding intensity constant to find the difference limen (DL) for frequency (based on the work of Shower & Biddulph, 1931), and then by holding frequency constant to find intensity difference limens (based on the work of Riesz, 1928). Stevens and Davis plotted on the area of audibility for normal listeners the number of discriminable units in squares ½ octave wide by 10 dB high. The upper left number in each cell gives the DLs for intensity, the upper right number gives the DLs for frequency, and the lower number gives their product, the total number of DLs in each cell. Adding the totals for each cell, Stevens and Davis estimated a grand total of 340,000 distinguishable tones in the audible range.

Figure 12 shows Kryter's (1984) version of the graph developed by Stevens and Davis. The lower, concave curves represent Kryter's estimated mean and 90% range of "critical intensities" present during everyday speech (curves labelled #4). Kryter estimates 43,093 discriminable units lie within this range. Curve #3 represents the audiogram of an individual with an average hearing threshold level of 15 dB for 500, 1000, and 2000 Hz. This person would have lost the capacity to perceive 16% (7,020) of the discriminable units constituting everyday speech, and about 4% (13,915) out of the total discriminable units. Curve #2 represents the audiogram of an individual with an average hearing threshold level of 25 dB at 500, 1000, and 2000 Hz. This person would have lost 31% (15,500) of the speech units, and 13% (44,082) out of the total discriminable units. Curve #1 belongs to a person with an average hearing threshold level of 55 dB at 500, 1000, and 2000 Hz, and a consequent loss of 96% (41,293) of the speech units, and 44% (150,000) out of the total number of discriminable units. Because there is a slight discrepancy between Kryter's estimate of the total number of units (350,000) and that of Stevens and Davis (340,000), Kryter's hearing loss estimates might be slightly lower if calculated on Stevens and Davis' total. The reader should

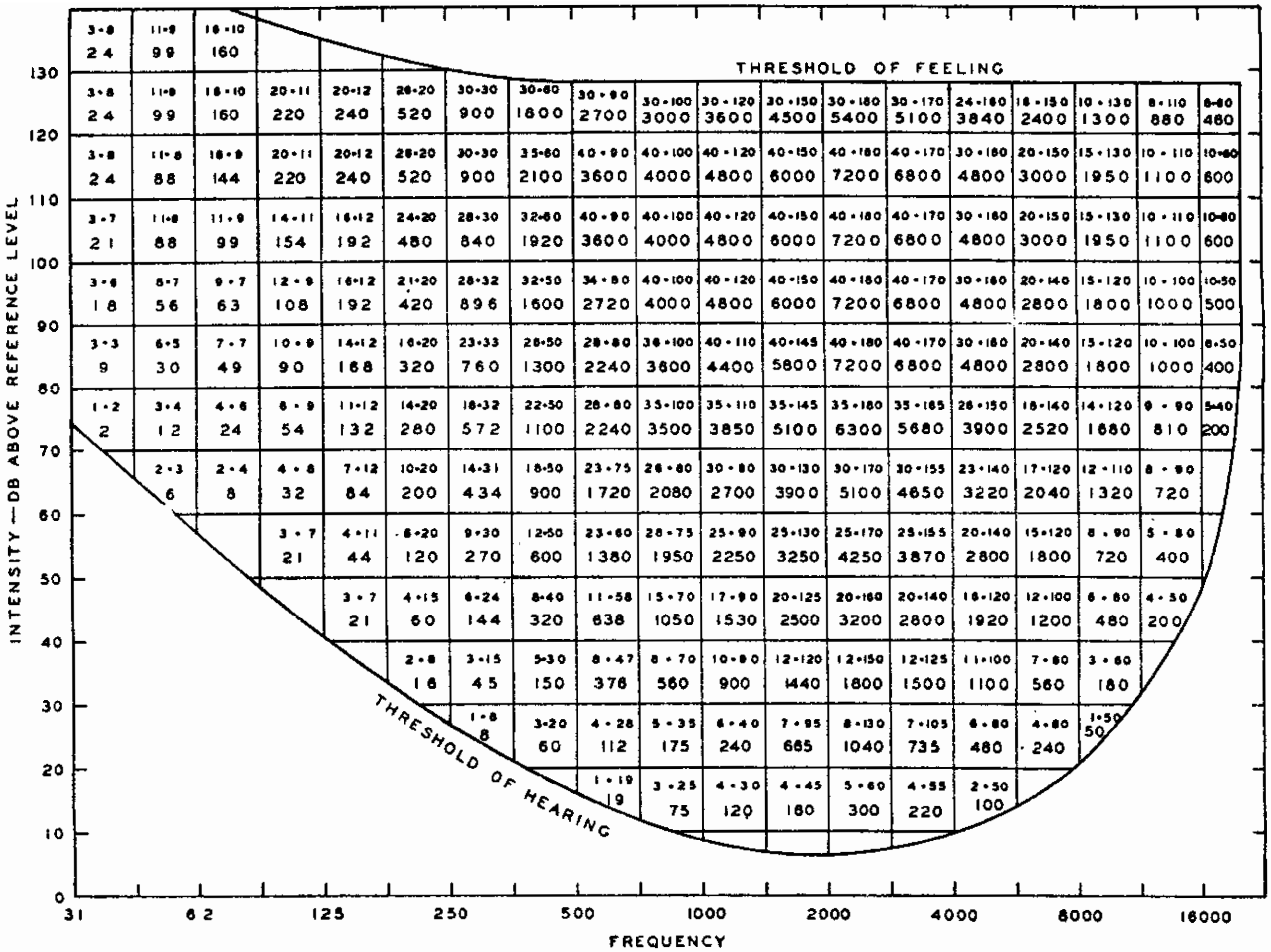

FIGURE 11. Number of distinguishable tones in the auditory area. (Stevens & Davis, 1983. Reprinted by permission.)

also note that these estimates are based entirely on a filtering model, and the situation might be somewhat different if the intensity, frequency, and temporal distortions present in many cochlear impairments were taken into account.

In another method of predicting the speech communication abilities of people with hearing impairment, Kryter (1970) calculates Articulation Index (AI) values corresponding to various amounts of hearing loss. Table 5 from Kryter (1970), shows AI estimates for several hearing threshold levels, based on the amount of speech expected to exceed thresholds of audibility for four levels of vocal effort. He has arrived at these estimates through a series of steps, which include subtracting 6 dB for the transition from earphones to sound field, and adjusting for the difference in threshold between pure tones and sounds having continuous spectra. According to Table 5, an individual with an average hearing level of 25 dB (ISO and ANSI) at 500, 1000, and 2000 Hz, which corresponds to a level of 35 dB at 1000, 2000, and 3000 Hz, will hear "everyday" speech (65 dB long-term rms) at an AI of 0.47, and will correctly hear 95% of the sentences and 73% of monosyllables presented. "Normal conversation" (55 dB long-term rms), will result in an AI of 0.26, with 68% sentences and 35% monosyllables recognized.

Certain other investigations have used the AI with hearing-impaired subjects. Macrae and Brigden (1973) tested 309 hearing-impaired subjects with CID sentences, in quiet and speech-to-noise ratios of +10 and −10 dB. In a manner similar to Kryter's, they calculated an AI for each individual subject, and found very high correlations between AI and sentence recognition scores. At the −10 dB speech-to-noise ratio, the correlation was 0.978 and at the +10 dB speech-to-noise ratio, it was 0.989.

In a slightly different approach, Smoorenburg et al. (1981) calculated the AI for normal listeners, based on the speech-to-noise ratio at which subjects achieved 50% sentence recognition (SRT). They then calculated the AI for each hearing-impaired subject, based on the speech-to-noise ratio corresponding to the subject's SRT and on the amount of information that would not be available because of the filter effect. Whereas the average AI for normal-hearing subjects in A-weighted noise levels of 40, 55, and 70 dB was 0.218, the average AI for hearing-impaired subjects was 0.248. Because the normal-hearing listeners

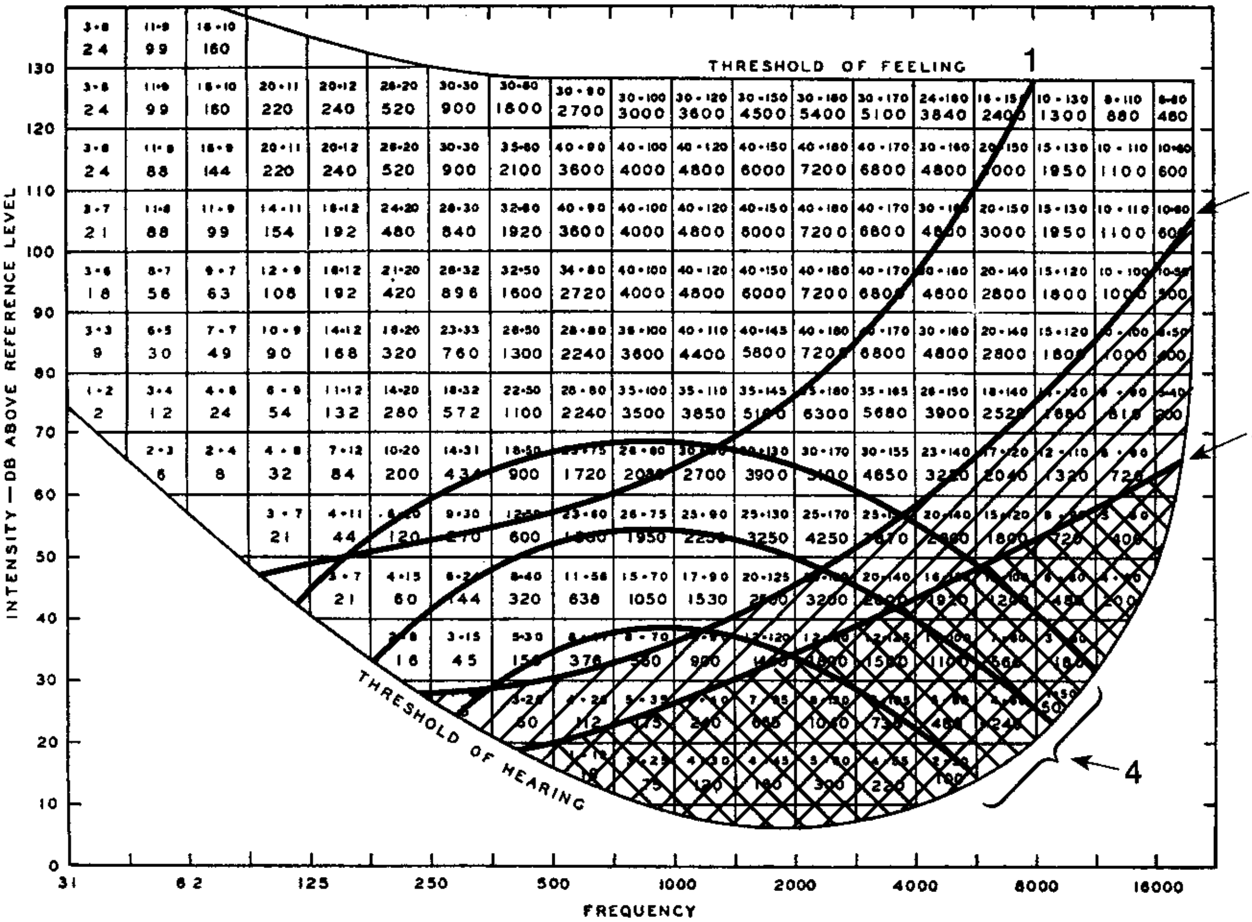

Figure 12. Number of discriminable units, as in Figure 11, with mean and 90% range of critical speech intensities, and three hypothetical audiograms superimposed. (Kryter, 1984. Reprinted by permission.)

could function at a slightly poorer AI than the hearing-impaired subjects (a difference in AI of 0.03), the authors conclude that reduction of audible cues does not completely explain the difference in performance between normal-hearing and hearing-impaired subjects.

Humes et al. (1986) have applied the AI and another index, the Speech Transmission Index (STI), to predict speech recognition scores by hearing-impaired subjects. After testing both indexes on a large amount of retrospective and some contemporary speech recognition data, they

Table 5. Articulation Index estimates for hearing threshold levels in four levels of vocal effort (from Kryter, 1970).

Avg. HL at 500, 1000 and 2000 Hz		*Avg. HL at 1000, 2000 and 3000 Hz*		*Weak conversational level in quiet (Long-term RMS = 50 dB)*			*Normal conversational level in quiet (Long-term RMS = 55 dB)*			*Everyday speech level (Long-term RMS = 65 dB)*			*Shouting level (Long-term RMS = 80 dB)*		
ASA	*ISO*	*ASA*	*ISO*	*AI*	*% Sent.*	*% 1000 PB Words*	*AI*	*% Sent.*	*% 1000 PB Words*	*AI*	*% Sent.*	*% 1000 PB Words*	*AI*	*% Sent.*	*% 1000 PB Words*
−5	5	5	15	0.81	99	94	0.84	100	95	0.98	100	98	1.0	100	100
5	15	15	25	0.56	97	81	0.72	98	92	0.84	100	95	0.98	100	98
15	25	25	35	0.34	87	52	0.47	95	73	0.72	98	92	0.84	100	95
25	35	35	45	0.17	36	17	0.26	68	35	0.47	95	73	0.72	98	92
35	45	45	55	0.03	5	2	0.09	15	8	0.26	68	35	0.47	95	73
45	55	55	65	0	0	0	0	0	0	0.09	15	8	0.26	68	35
55	65	65	75	0	0	0	0	0	0	0	0	0	0.09	15	8
65	75	75	85	0	0	0	0	0	0	0	0	0	0	0	

concluded that the best predictor involved a combination of the two methods. The resulting index, the modified (or m) STI, incorporates the AI's ⅓-octave band analysis and its original (French & Steinberg) weighting factors, and the STI's inclusion of temporal fluctuations in the speech and noise signals.

2.4 PERCEPTION OF WARNING SIGNALS

Very little research has been conducted on the ability of people with hearing impairment to detect and recognize auditory warning signals. What little has been done has focused on the effect of hearing loss in combination with hearing protectors. Wilkins (1984) carried out a field study to assess the effects of hearing protectors and hearing loss on the perception of warning sounds in an industrial environment. He used two warning signals, the sound of a horn on a forklift truck and the clinking sound of metal pieces spilling from a container. Subjects with "substantial" hearing loss gave 18% fewer responses to the clinking sound than others with normal and only mildly impaired hearing, but both groups responded similarly to the sound of the horn. Wilkins attributes this to spectral differences in the signals. Because many (but not all) of the subjects wore hearing protection, and because of numerous other uncontrolled variables, any conclusions from this study should be made with extreme caution.

Another neglected research area is the effect of hearing impairment on the perception of important environmental sounds, such as combat sounds. Examples would include the sound of footfalls, barbed wire being clipped, and the insertion of a rifle magazine. Popular opinion holds that many of these sounds are predominantly high-frequency, with energy in the 2000–6000 Hz range (e.g., Aspinall & Wilson, 1986). However, Price and Hodge (1976) have shown that most spectra of these types of sounds are fairly flat.

Price and Hodge (1976) developed a model for predicting the detectability of various noises. They analyzed 24 noise samples according to the sound energy in critical bands, then modeled the normal ear's method of integrating energy over 20-msec and 200-msec periods. Actual and predicted detection thresholds showed excellent agreement. On comparing typical audiograms of noise-exposed soldiers to the 24 noise spectra, they estimated that normal hearing individuals could detect these sounds at an average level 16 dB lower than soldiers with about 20 years of noise exposure. With the introduction of high-frequency environmental noise (jungle with animals and insects), the estimated difference between the two groups fell to 0.3 dB. A low-frequency environmental noise (recorded in rural France) produced an estimated difference of 7.8 dB between normal-hearing listeners and soldiers with 20 years of noise exposure. The authors explain that the reason why these differences are not greater is because listeners would be relying largely on mid-frequency hearing to make most of the detections. They cautioned, however, that detection and identification are not the same, and that people with hearing impairment are likely to have more difficulties in analyzing sound than their normal-hearing counterparts. From the preceding discussions of suprathreshold abnormalities, it would appear that this caveat is warranted.

2.5 SUMMARY

2.5.1 Effects of Hearing Loss on Speech Recognition

There is no question that high-frequency hearing loss, typical of noise-induced hearing loss and presbycusis, acts as a low-pass filter. There is still some debate on the extent to which distortion within the auditory system further degrades the ability to hear speech, but today this appears to be a matter of degree of distortion rather than a matter of whether this distortion exists. There is also little doubt but that people with a significant degree of the distortion component need more favorable speech-to-noise ratios, perhaps up to 10 dB more favorable, than their normal-hearing counterparts.

Distortions of the auditory system that interfere with speech recognition can be divided into categories of frequency, intensity, and temporal processing. The frequency distortions most commonly implicated are broadened tuning curves and upward spread of masking, but others, such as harmonic distortion, have been identified. Intensity distortions, such as recruitment, abnormal intensity discrimination, and limited dynamic range have also been shown to have deleterious effects on speech, as have distortions of temporal processing, such as abnormal effects from temporal summation, forward and backward masking, and gap detection.

Investigations have shown that hearing-impaired subjects benefit from the advantages of binaural hearing, but not as much as normal-hearing listeners. On the basis of limited data, it appears that hearing-impaired subjects have only minor difficulties localizing sound in the horizontal plane, but they may have trouble identifying the source of a sound in the vertical plane.

2.5.2 Hearing Handicap

The terms *handicap, impairment, disability,* and *material impairment* are often used interchangeably, but carry different meanings. For this report, the preferred term is *handicap,* which is used to mean the disadvantage imposed by an impairment sufficient to affect one's personal efficiency in the activities of everyday living.

Most studies of speech recognition in quiet point to the importance of good hearing in the mid-frequency range. Virtually all of the studies of speech recognition in noise show the importance of high-frequency hearing. The same is true of speech that is distorted, for example, by speeding or reverberation. Recent investigations of the "low fence" or point of beginning handicap indicate an average hearing threshold level between 15 and 30 dB for the frequencies 1000, 2000, and 3000 Hz. This is for "everyday" speech, usually with varying amounts of background noise. The actual level of the low fence will depend mainly upon the difficulty of the specific listening task. Special consideration must be made for circumstances requiring the identification of faint or high-frequency sounds, in which case the criterion for hearing sensitivity in the high frequencies should be more stringent.

2.5.3 Predicting Communication as a Function of Hearing Impairment

An estimate of the effect of hearing impairment on speech communication can be made on the basis of audible discriminable units in the speech range, according to a method devised by Kryter (1984). Estimates can also be made with the use of the Articulation Index. Both of these methods model the hearing mechanism as a frequency filter, necessitating an added correction for the distortion component.

2.5.4 Warning Signal Identification

Very little research has been conducted on the ability of hearing-impaired listeners to detect and recognize auditory warning signals. Research on listeners with essentially normal hearing and on the estimated responses by hearing-impaired listeners indicates that detection differences between the two groups are not very large. These differences may turn out to be greater for actual signal recognition than they are for detection.

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Chapter 3

The Effects of Hearing Protectors on the Perception of Speech and Warning Signals

High levels of noise necessitate the wearing of hearing protection by a large number of personnel in many different military and industrial environments. It is often necessary to communicate and to hear warning signals while wearing hearing protectors in most of these environments. Traditionally, hearing conservation professionals have informed hearing protector users that these devices will not interfere with the ability to hear speech and warning signals, and in some cases, may even enhance the audibility of desired signals. The response of the users, however, is not always so optimistic. This section reviews and analyzes the research on this issue so as to gain a more thorough understanding of the effects of hearing protectors on speech and warning signal perception and to make recommendations for further research where knowledge gaps still exist.

Many reports on the effects of hearing protectors on speech and signal communication are prefaced by descriptions of complaints by users. Surveys and questionnaires indicate that many soldiers and industrial workers dislike hearing protection, for whatever reason. In their study of hearing loss among 3,000 Army personnel in the infantry, armor, and artillery branches, Walden and his colleagues found that only 64% of the soldiers sampled said they used hearing protectors, and about 50% of the sample reported that they disliked them (Walden, Prosek, & Worthington, 1975). Although users dislike hearing protectors for numerous reasons, one of the most common reasons is interference with communication and the perception of warning signals.

A study by the British National Coal Board found, after a 1-week trial period of hearing protectors, that 45% of the workers believed that hearing protectors "blocked" or "slightly blocked essential sound" (NCB, 1975, cited in Wilkins & Martin, 1977). Two thirds of these responses came from personnel who had been wearing earmuffs rather than earplugs. Wilkins and Martin (1982) cite six studies to show that approximately half of the workers who wear hearing protection think they have more difficulty hearing warning sounds with protectors than without them.

There is no doubt that under certain conditions hearing protectors can actually improve the recognition of speech and warning signals in noise. Such improvements tend to occur in noise levels above 80–90 dB (Kryter, 1946; Lindeman, 1976; Chung & Gannon, 1979), when only the listeners (not the talkers) are wearing protection (Kryter, 1946), and for listeners with normal hearing (Abel, Alberti, Haythornthwaite, & Riko, 1982; Chung & Gannon, 1979; Lindeman, 1976; Rink, 1979).

3.1 THEORETICAL CONSIDERATIONS

The theory behind this improvement in high noise levels is that the protectors attenuate both the noise and the desired signal by equal amounts, thereby reducing the likelihood of auditory distortion, which tends to occur at high listening levels. This distortion has been attributed to a broadening of the auditory filter at high stimulus levels (Coleman et al., 1984; Wilkins & Martin, 1977), causing proportionately greater disruption by noise masking. The improvement sometimes experienced with hearing protectors may also be due to the nonlinear growth of masking, which is especially evident in sound pressure levels above about 80 dB (see Coleman et al., 1984). Because the protectors equally reduce the noise and speech components in a given frequency band, no spectral information should be lost, and the reduction in distortion and masking promotes better listening.

The situation, however, is not always this satisfactory. Most hearing protectors do not attenuate all frequencies equally, but tend to reduce high-frequency sounds considerably more than those of low frequencies. Thus, the spectral characteristics of the signal have been changed, giving the low-frequency energy more opportunity to mask the high-frequency components. According to Lazarus (1983a), the greater the per-octave attenuation slope of the hearing protector, the greater will be the loss of signal audibility. The audibility of signals may be especially poor when the noise is mostly low and mid-frequency and the signal is higher. Lazarus also reports that changes in the signal's temporal characteristics may occur because of resonance changes beneath the protector and because of nonlinear properties of the material (Lazarus, 1983a).

These problems are exacerbated when the hearing protector user is hearing impaired. In this case, even a protector with relatively flat attenuation simply may reduce the level of the signal to below the listener's hearing threshold level. This condition will, of course, be more likely to occur when the protector's attenuation is significantly greater in the high frequencies, which is often the case. Figure 13, from Lazarus (1983a), shows the effect of a hypothetical earmuff's attenuation on signal audibility with a normal listener (N) and one with a high-frequency sensorineural hearing loss (S). Although the protector might actually have enhanced signal detection for the normal-hearing listener, it attenuated the signal beneath the hearing threshold levels of the person who was hearing impaired at nearly all frequencies.

3.2 EFFECTS OF HEARING PROTECTORS ON SPEECH COMMUNICATION IN NORMAL-HEARING AND HEARING-IMPAIRED LISTENERS

3.2.1 Speech Recognition by Normal-Hearing Listeners

At low and moderate noise levels, hearing protectors impede speech recognition, even with normal-hearing lis-

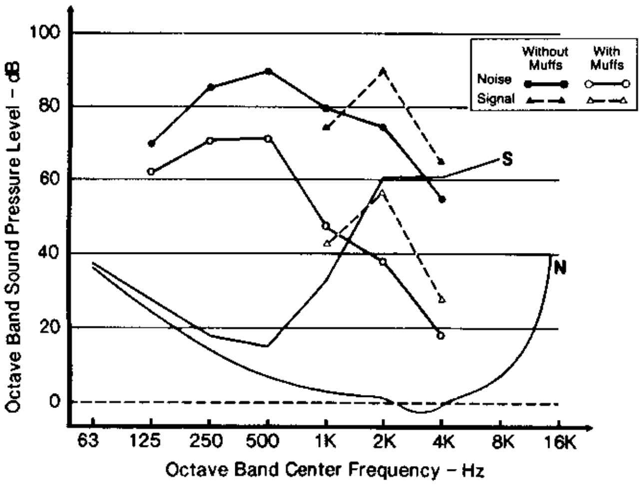

FIGURE 13. Effect of earmuffs on the audibility of a signal in noise by a subject with normal hearing (N) and one with sensorineural hearing loss (S). Upper curves show octave band levels of signal and noise without muffs; lower curves represent levels with muffs. (Lazarus, 1983. Reprinted by permission.)

teners, because they reduce the audibility of important consonant cues. For this reason, the continuous use of hearing protectors during intermittent noise exposure can be a problem. At certain noise levels, however, protectors begin to be advantageous for normal-hearing users, depending on the speech and noise conditions.

In one of the earliest experiments of its kind, Kryter (1946) administered PB words over a public address system in simulated engine-room noise having a negative 5-dB per-octave slope. Subjects wore the V-51R earplugs. The results showed that in background sound pressure levels between 75 and 85 dB, earplugs enhanced speech recognition, and below that level they impeded it. Figure 14 contains a replotting of Kryter's data by Acton (1967), showing the relative advantage and disadvantage between the plugged and open-ear conditions for the 50% word recognition score in the occluded condition. The crossover point appears to be just below 80 dB. This finding is consistent with the 80–dB level cited by Coleman et al. (1984) for the prevention of disruptive effects from the nonlinear growth of masking. In a masking noise level of 88 dB SPL, Michael (1965) found that earplugs slightly enhanced speech recognition, especially at more favorable speech-to-noise ratios. Approximately the same (88–dB) crossover level was found in a small study by Acton (1967) using monosyllabic words in white noise.

In a study of hearing protector use with a speech communication system, Pollack (1957) used broadband noise of approximately 70–130 dB SPL. Subjects used the V-51R plugs and wax-impregnated cotton. For fixed speech-to-noise ratios, word recognition scores were approximately the same for the protected and unprotected conditions, up to 100 dB at 0 dB speech-to-noise ratio, and up to about 112 dB at +12 dB speech-to-noise ratio, above which levels hearing protectors enhanced performance. With variable speech-to-noise ratios, using an automatic gain control system, earplugs provided even larger improvements at all noise levels tested (100 dB and above).

Other investigations, which have not necessarily intended to identify a specific crossover level, have lent support to the finding that hearing protectors improve speech recognition above certain noise levels for normal-hearing users. For example, a study by Williams, Forstall, and Parsons (1970) showed that normal-hearing listeners recognized monosyllables read in a loud voice more successfully when wearing earplugs than with unoccluded ears. The study involved high levels of aircraft noise (about 116 dB SPL), both in laboratory and field conditions. In another investigation, Howell and Martin (1975) tested speech recognition at various speech-to-noise ratios and found that scores improved with the wearing of earplugs in levels over about 80 to 95 dB.

Lindeman (1976) found that normal-hearing and very slightly impaired listeners also benefitted by wearing earmuffs while listening to monosyllables at 90 dB in white noise at 80 dB SPL. Rink (1979) used a 350–2800 Hz band of noise at 90 dB(A) to test the effects of earmuffs on the recognition of speech at 85 dB(A) in quiet (65 dB(A)) and in noise. In quiet, normal listeners performed about the same with and without hearing protectors. In noise, their performance improved with protectors. Chung and Gannon (1979) also report an improvement with earmuffs in noise levels of about 90 dB SPL and a speech-to-noise ratio of +10 dB, but not at a speech-to-noise ratio of −5 dB. They report degraded speech recognition in noise levels of about 65 dB SPL at both speech-to-noise ratios tested (+10 and −5 dB). Abel and her colleagues (1982) found virtually no effect of plugs and muffs on speech recognition by normal listeners in noise levels of 85 dB(A) and speech-to-noise ratios of +5 and −5 dB.

Taken together, these studies point to an enhancement effect above about 80 to 90 dB, which tends to increase both with increasing noise levels and with speech-to-noise ratio. This enhancement appears to be reduced with negative speech-to-noise ratio, and hearing protectors begin to produce an adverse effect in noise levels somewhere below

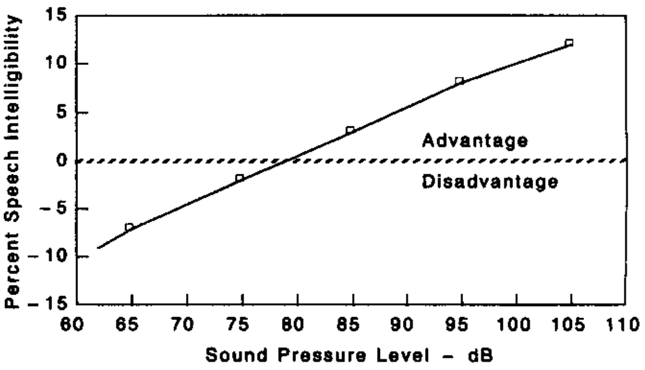

FIGURE 14. Advantage and disadvantage of wearing earplugs as a function of background sound pressure level. Data points represent occluded speech intelligibility relative to the 50% score in the unoccluded condition. (Kryter, 1946, and Acton, 1967. Reprinted by permission.)

about 80 to 90 dB. Numerous other factors that lead to a negative effect will be explained in the following paragraphs.

3.2.2 Speech Recognition by Listeners With Hearing Impairment

Hearing protector users have not always acknowledged the beneficial effects on communication, especially those who have worked in noise environments for long periods of time. One significant reason for dissatisfaction among personnel with many years of noise exposure is probably that they have developed impaired hearing. Over recent decades, researchers have focused their attention on the effects of protectors on users with varying degrees of hearing impairment. For example, Frölich (1970) noted that senior aviators with high-frequency sensorineural hearing losses did not receive benefits from earmuffs when presented with digits (names of numbers) in noise levels greater than 100 dB.

Many of the investigations mentioned previously in the discussion of speech recognition by normal-hearing users included the effects on people with impaired hearing as well. Of Lindeman's 537 Dutch factory workers, most had some amount of noise-induced hearing loss (Lindeman, 1976). The results showed that subjects with fairly good high-frequency hearing (average hearing levels at 2000, 3000, and 4000 Hz no worse than about 25 dB) experienced a slight benefit from wearing earmuffs, but those exceeding an average of about 30 dB performed less well in the protected condition. The greater the hearing loss at these frequencies, the greater was the deterioration of performance.

Rink (1979) compared the performance of 30 hearing-impaired subjects with that of 10 with normal hearing, using speech levels of 65 dB(A) in quiet and 85 dB(A) in noise at a speech-to-noise ratio of −5 dB. Unfortunately, the author gives little information on the magnitude of the hearing impairments except that they were at least 30 dB at two or more frequencies from 250 to 8000 Hz. Ten of the subjects were presbycusic, 10 had noise-induced hearing losses, and 10 had sensorineural losses of unknown etiology. In the quiet condition, normal-hearing listeners performed equally well with and without earmuffs (as reported above), and the hearing-impaired individuals performed more poorly. In noise, the performance of the normal-hearing listeners improved with protectors, and the hearing-impaired listeners performed about the same with and without protectors.

Chung and Gannon (1979) investigated the effects of earmuffs on monosyllable recognition in pink noise delivered at sensation levels of 40 and 65 dB. These levels translated to about 65 and 90 dB SPL, respectively, for normal-hearing subjects, and would have been higher for hearing-impaired subjects according to their speech reception thresholds. The group of 100 subjects included 60 individuals with a history of noise exposure, divided into categories of mild, moderate, or severe high-frequency impairments. Speech-to-noise ratios tested were +10 and −5 dB. The results showed poorer performance with earmuffs for all conditions except for the normal listeners at high sensation levels (about 90 dB). Performance tended to deteriorate with increasing high-frequency hearing loss, which is to be expected, and also in the more favorable speech-to-noise ratio, which is contrary to some of the findings mentioned previously for normal-hearing listeners. However, speech recognition scores in the −5 speech-to-noise ratio condition may have been influenced by truncation effects. The authors noticed an interesting difference at the −5 speech-to-noise ratio between response errors in the protected and unprotected modes. With protectors, most of the errors resulted from a failure to respond, whereas in the open condition they were due to an incorrect answer. According to the authors, the former error suggests that hearing protectors often attenuate the signal to inaudible levels, but without protectors the speech signal tends to become distorted by loud noise (or is itself distorted).

In another large study of the effects of hearing protectors on speech recognition, Abel et al. (1982) used subjects with mild-to-moderate, flat hearing losses, in addition to subjects with high-frequency (noise-induced) losses and those with normal hearing. The 96 subjects were also divided into fluency categories according to whether English was their native language. Subjects listened to monosyllables at 80 or 90 dB(A) in quiet, white noise, or taped "crowd" noise at a constant level of 85 dB(A). Hearing protectors consisted of earmuffs, formable plugs, and premolded plugs. The results showed that although hearing protectors had virtually no effect with normal-hearing listeners, those with both kinds of hearing losses performed significantly more poorly with hearing protectors than without them. The difference in word recognition ranged from 10% to 50% depending on the fluency factor and the background noise condition. The nonfluent subjects scored about 10% to 20% lower than the native English speakers, but the effect was independent of protector condition. In addition, subjects scored lower in the simulated crowd noise than in white noise, but this effect was also independent of the open or occluded ear condition. Differences in speech recognition scores among the six protectors were not great, but one of the two muffs tested caused a reduction in scores that was somewhat greater than the other five protectors. Speech recognition by subjects with flat hearing losses was considerably more severely affected by hearing protectors than that of subjects with high-frequency losses.

3.2.3 Effects of Visual Cues, Talker's Ear Condition, and Type of Protector

Certain other parameters are also important in the degree to which hearing protectors affect speech recognition. These include the availability of visual cues, whether the talker is wearing hearing protection, and the type of protector.

3.2.3.1 *Visual cues.* Person-to-person communication can improve speech recognition by the added advantage of visual cues. Rink (1979) found that both hearing-impaired and normal-hearing listeners performed better with visual cues, regardless of protector conditions, when listening in a noisy background. Martin, Howell, and Lower (1976) found an increase of about 30% in high noise levels, because of the introduction of visual cues. The investigators found that visual cues actually decreased the differences between the occluded and unoccluded conditions.

3.2.3.2 *Talker's ear condition.* Another important variable is the ear condition of the talker: whether the talker wears protectors. Individuals whose ear canals are occluded by hearing protectors, impacted earwax, or some other cause, will experience the "occlusion effect." This means that these individuals hear their voices by bone conduction, and the subjective impression is that their voices sound louder than they do by the normal air conduction route. The natural inclination is to speak more softly, at least in a noisy background.

According to Berger (1986), the magnitude of the occlusion effect varies according to the fit of the occluding device. Ear protectors that seal the entrance of the canal, such as "semiaurals" or "canal caps," provide the most occlusion effect, and deeply inserted plugs provide the least. Muffs with a small volume of air under the earcups will produce somewhat more occlusion effect than large-volume muffs. As the occlusion effect increases, it follows that voice level would decrease.[4]

During person-to-person communication in a reverberant room, Kryter (1946) found that hearing protectors produced a decrease of 1 to 2 dB in the talker's voice level. This fact lead to slightly lower speech recognition scores on the listener's part. In fact, when both talker and listener wore protection, the crossover point between disadvantage and advantage did not occur until about 105 dB (Kryter, 1946).

Howell and Martin (1975) also investigated the effects of hearing protection on talkers' voice levels and consequent speech recognition by listeners. This time there were no visual cues. They found that when talkers wore earmuffs, voice levels were reduced by an average of 2.7 dB, and with earplugs, the average reduction was 4.2 dB. This reduction occurred in high noise levels (93 dB), but not in quiet (54 dB). In high noise levels, listeners' speech recognition scores improved in the occluded condition. However, they were reduced considerably when the talker wore protection, with average scores falling from 56% to 31%, wiping out the gains that hearing protectors had provided when only the listener had worn protection. The authors noted that this reduction was more than would have been expected from the reduction in voice level alone. They suggested that individuals wearing hearing protection may also talk less distinctly, and that their speech may become distorted from hearing their own voices through bone conduction (Howell & Martin, 1975).

In a follow-up investigation, Martin et al. (1976) assessed spectral differences in voice quality between occluded and unoccluded conditions. Their spectral analysis is reproduced in Figure 15, which shows significant differences between speech levels in the open and protected conditions (about 2 to 3 dB(A)), but no significant differences in frequency content. To see if wearing hearing protectors produces subtle changes in voice quality and consequent speech intelligibility decrements, Martin and his colleagues mixed speech recorded by a talker in hearing protectors with noise. They then used speech from unoccluded talkers at the same speech-to-noise ratio, and compared the resulting speech recognition scores. There was no significant difference. Thus, the authors were unable to explain the extreme degradation from the previous experiment (Howell & Martin, 1975).

Hörmann, Lazarus-Mainka, Schubeius, and Lazarus (1984) studied the effects of hearing protectors on speech communication in terms of a number of dependent variables, which included speech tempo and speed of communication in addition to speech level and intelligibility. They studied a total of 360 talkers and listeners, unoccluded and using foam earplugs, in pink noise at 76, 84, and 92 dB(A). Speech materials consisted of monosyllabic words, sentences, text from a newspaper, and picture stories (cartoons) that the talker described. Talkers and listeners were separated by a translucent curtain to preclude visual cues. Under certain conditions, listeners provided feedback to the talkers on the extent to which they understood the talkers' communications. The results showed that average speech levels dropped by 4 dB in the 92-dB(A) noise level, which confirms the similar finding of Howell and Martin (1975), but was slightly greater than the 2–3 dB drop found by Martin et al. (1976). The investigators also noted, in the 92-dB(A) condition, that talkers wearing earplugs articulated significantly faster and paused about 25% more briefly between words and phrases. The speed of information exchange, which is a measure of the listener's reaction time, decreased with increasing noise level and when both talkers and listeners wore protectors.

Speech recognition scores, pooled for all speech materials, are shown in Figure 16, from Hörmann et al. (1984). One can see that earplugs worn by either the talker or listener tended to degrade communication for virtually all of the experimental conditions. Surprisingly, earplugs worn by the listener only failed to improve communication at the highest noise level, although they did improve it somewhat at the 84-dB(A) level. The poorest performance on the speech recognition task occurred when both talkers and listeners wore protectors, which is most characteristic of real-life conditions. The use of feedback, in the form of either verbal communication or a signal light, improved speech recognition scores considerably, as can be seen in Figure 17. When both talker and listener wore earplugs, scores were almost as high as when both were unprotected, at least when the feedback consisted of verbal responses. When the feedback was in the form of a signal light, scores

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[4] Berger also reports that the reduction in speech level occurring when talkers wearing hearing protectors communicate in noise does not take place in quiet (Berger, 1988). He observed that although the bone-conducted speech is still amplified by the occlusion effect, individuals monitor their speech levels by listening to the airborne component, which has been attenuation by the hearing protection device. To overcome this perceived reduction in speech level, the tendency is to raise one's voice.

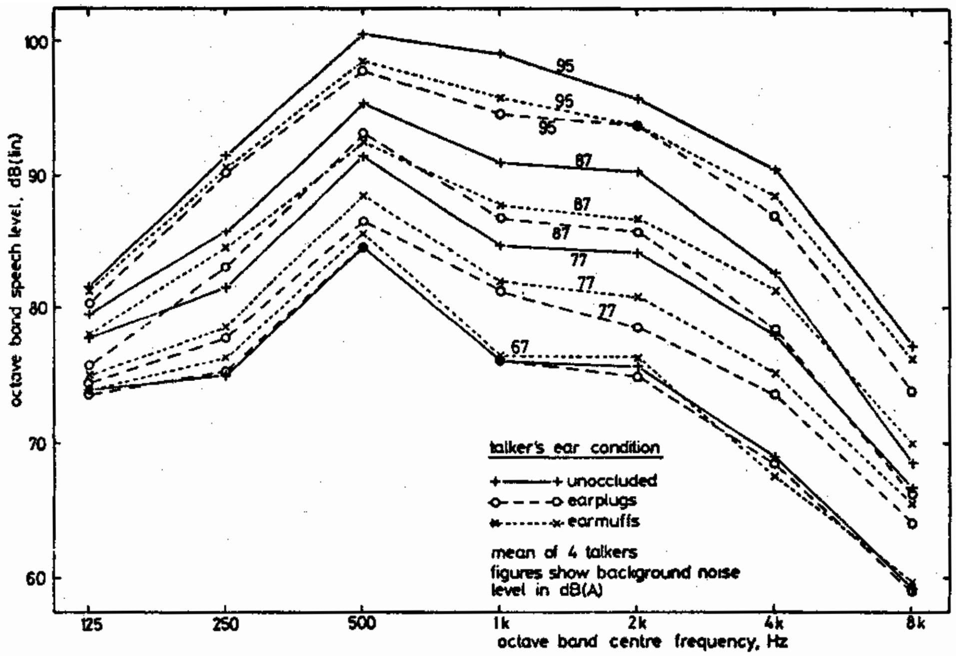

FIGURE 15. Mean octave band speech levels for levels of background noise from 67 to 95 dB(A). Talkers are unoccluded (+), with plugs (O), or with muffs (×). (Martin, Howell, & Lower, 1976. Reprinted by permission.)

were somewhat lower, but still much improved over the no-feedback condition. Hörmann and his colleagues believe that their experimental conditions are comparable to those found on the job, even the reduced eye contact produced by the translucent curtain, and the 1.5-meter distance between talker and listener. The authors conclude that industrial workers reject ear protectors ". . . not for some unclear, ill-defined reason, but rather for reasons which can be statistically supported—the impairment of speech intelligibility and deficiency in verbal communication" (p. 77).

In an experiment with a somewhat different purpose, Eriksson-Mangold and Erlandsson (1984) investigated the psychological and social effects of "sudden hearing loss" by occluding the ears of normal-hearing individuals. Subjects wore earplugs or material used in making earmolds for 9½ hours, while they engaged in their normal daily activities. The results of a subsequent questionnaire revealed that 28% felt that the distortion of their own voices (by bone conduction) was the factor that most influenced them during the experiment. Interestingly, 57% of the subjects reported considerable inhibition in speaking because they could not control the loudness of their voices. Because the subjects were presented with such categories as "distortion of own voice" and "distortion of laughter, coughing or chewing," the responses were not purely spontaneous. However, a 5-point rating scale allowed the authors to assess the importance of each factor, and it appears that voice distortion and loudness control were significant factors.

3.2.3.3 *Type of protector.* Certain investigations have included more than one type of hearing protector, and the results sometimes indicate a difference in effect on speech communication. As mentioned above, Abel et al. (1982) used six protectors, consisting of various kinds of plugs and muffs. The results showed that one of the two muffs caused a greater reduction in speech recognition than the other protectors. Howell and Martin (1975) used the V-51R earplug and the Welsh 4530 earmuff. Both protectors gave comparable attenuation in the low frequencies, but the earmuff afforded much greater attenuation at 500 and 1000 Hz and slightly greater attenuation at 2000–6000 Hz than the plug. The investigators found that plugs allowed consistently better speech recognition than muffs, especially in the highest noise condition, which they attribute to the earplug's lower attenuation values in the middle and high frequencies.

3.3 EFFECTS OF HEARING PROTECTORS ON WARNING SIGNAL PERCEPTION

3.3.1 Signal Detection

The same kinds of theoretical conditions that apply to speech communication with hearing protectors also should apply to the perception of nonverbal stimuli. The principal difference, of course, is that there is likely to be more variation in the acoustical parameters of nonverbal signals. In general, however, one would expect that in high levels of signal and noise, hearing protectors would attenuate both the signal and the noise to more moderate listening levels, thus improving audibility. Evidently, this is what has occurred in a number of experiments.

Levin (1980) used recorded mining noises at levels

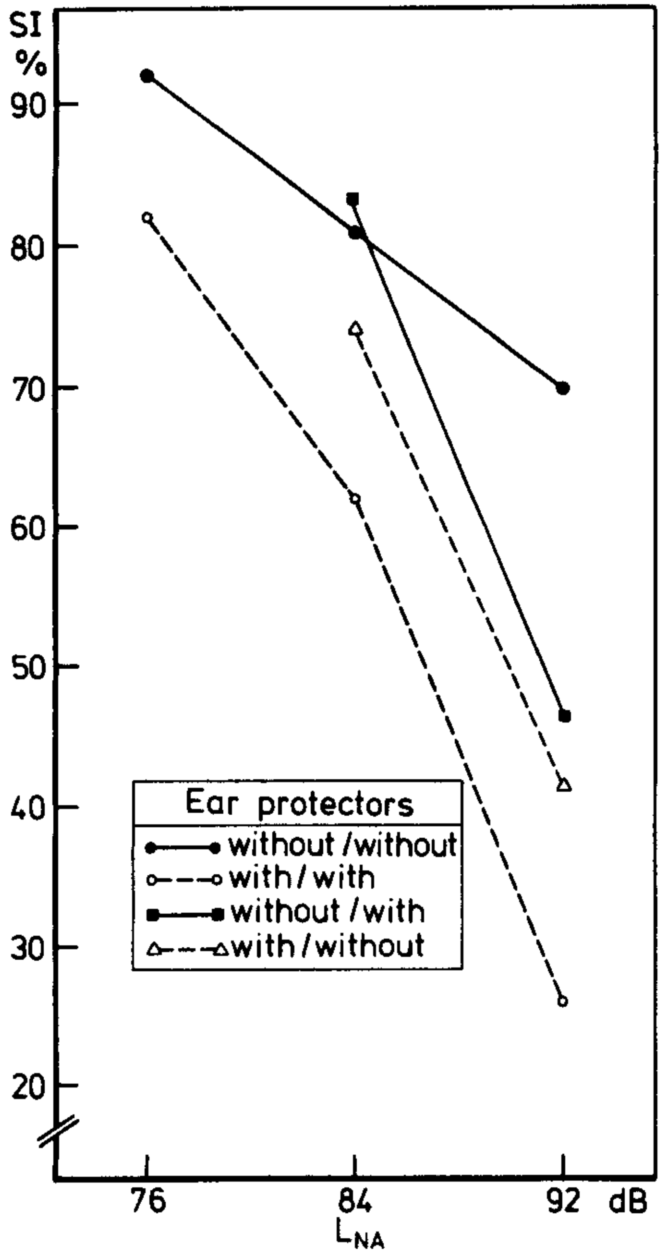

FIGURE 16. Speech recognition scores (SI) for various kinds of speech stimuli as a function of A-weighted noise level and ear condition (with or without protectors). In the legend, the listing is talker/listener. (Hörman, Lazarus-Mainka, Schubeius, & Lazarus, 1984. Reprinted by permission.)

greater than 90 dB to determine thresholds for pure tones in listeners who wore hearing protectors. He found that for most noises, masked thresholds were the same or lower (better) with hearing protectors than without them, and there was less variability among subjects' scores in the protected condition.

In an elaborate investigation of signal detection in mining noises, Coleman et al. (1984) assessed masked threshold for pure tones among 27 mine workers with varying degrees of hearing loss. Conditions investigated were no protection, circumaural protectors with headband, helmet-mounted circumaural protectors, and foam plugs, in noise levels of approximately 90 dB(A). The investigators also tested a method of predicting masked thresholds using a formula based on a modification of critical band theory developed by Patterson, Nimmo-Smith, Weber, and Milroy (1982). The method employed the level and spectrum of the background noise, absolute threshold levels of each subject, estimations of the "filter width" of each subject, and hearing protector attenuation values. The results showed that the use of hearing protectors had no significant effect on *mean* masked thresholds of audibility for pure tones above 1000 Hz, but they did cause an increase in the *range* of thresholds, especially for the frequencies above 2000 Hz and in listeners with the poorest hearing. Consequently, the investigators recommended the use of warning signals with primary spectral energy in the frequencies below 2000 Hz for the benefits of these listeners. Coleman et al. also found a significant increase in masked thresholds for frequencies between 500 and 1000 Hz when subjects wore earmuffs, but not with the foam plugs. Predicted masked thresholds were somewhat higher than ac-

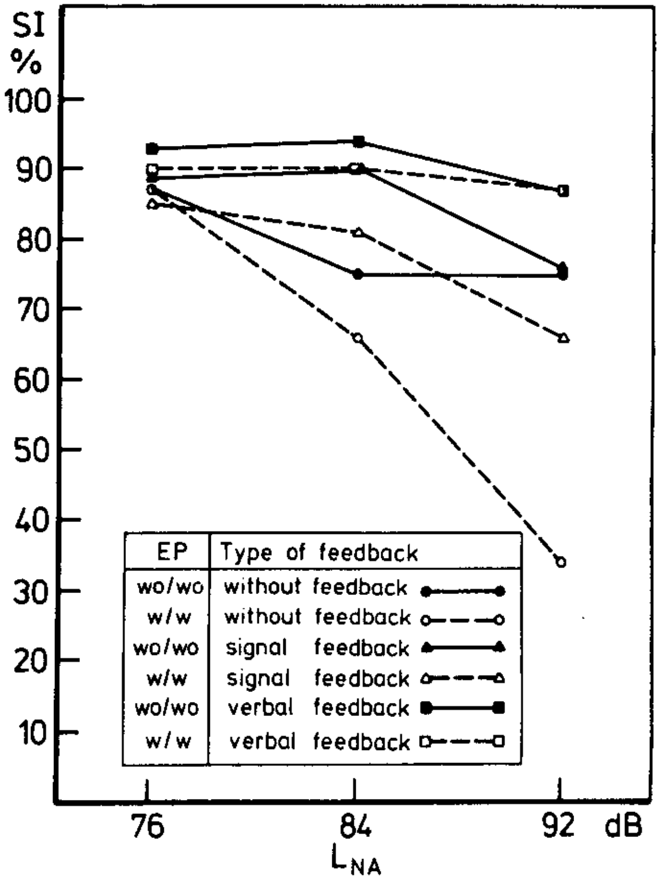

FIGURE 17. Speech recognition scores (SI) as a function of A-weighted noise level, ear condition (with and without protectors), and three feedback conditions. In the legend, EP = ear protection, and WO/WO = talker without and listener without. (Hörman, Lazarus-Mainka, Schubeius, & Lazarus, 1984. Reprinted by permission.)

tual thresholds, although the method consistently predicted the general pattern of responses. With minor adjustments, it appears that this prediction method could be used in practical circumstances.

In another study, Forshaw (1977) used broadband noise at 88 dB(A), either with or without line components, to simulate ships' engine and boiler rooms. Three normal-hearing subjects and one with a high-frequency hearing loss attempted to detect six pure tones between 1000 and 6000 Hz. In the continuous-spectrum background noise, normal-hearing subjects performed generally better in the protected condition. In the broadband noise with line components, however, the reverse appeared to be true. The hearing-impaired subject gave about the same performance in the protected and unprotected conditions, except that the 3000-Hz signal was attenuated beneath the threshold of audibility when the subject wore protectors. Although the investigation is severely limited by its small subject population, it suggests that protectors may affect signal detection much the same way they affect speech recognition, enhancing performance in high noise levels with normal listeners, but being a potential source of problems for hearing-impaired listeners.

Wilkins and Martin performed a series of experiments on the effects of hearing protectors on the perception of warning signals by normal-hearing listeners (Wilkins & Martin, 1977, 1981, 1982, 1984, and 1985). In the first of these experiments (Wilkins & Martin, 1977), 16 subjects listened for a wailing "high-low" siren and a bell at 75 and 95 dB SPL mixed with random noise, with ears unoccluded and while wearing muffs or plugs. Another ear condition was provided by a spectrum-shaper, which was used on the signal-plus-noise mixture to simulate the mean attenuation provided by the earmuffs. The results showed no large effect of ear condition on masked threshold level, although in the 95-dB noise level, the three protected conditions produced lower (better) detection thresholds than the unprotected condition. Detection thresholds were somewhat lower for the bell than for the siren, and this difference appeared to be unrelated to ear condition at the 95-dB level. At the 75-dB level, however, subjects performed slightly better in the unprotected condition, which is not surprising in light of the 80–90-dB crossover levels discussed previously. Also, there were only minor differences between performance with the plug and the muff, even though there were considerable spectral differences between them, with the mean attenuation of the muff approximately 20 dB greater than that of the plug at 1000 Hz.

Some investigators report that hearing protectors can degrade the ability to detect warning sounds. Lazarus (1979) tested the effects of wearing earmuffs on the ability of 25 subjects to identify bands of noise at approximately 85 dB(A) with differing spectra. The per-octave slopes of the five noises ranged from −12 to +12 dB. Subjects learned to identify the noises before the test, then listened with and without hearing protection. No competing noise was present. The results showed significantly fewer correct responses with protectors than without.

Subsequent investigations by Wittmann and Lazarus (1980) and Lazarus, Wittman, Weissenberger, and Meissner (1983) (as reported by Lazarus, 1983b) used a signal called a "Typhon" at 76 to 96 dB(A) embedded in noise levels of 80 to 105 dB(A). The Typhon signal is used to warn rail track workers against approaching trains. Subjects included normal-hearing and hearing-impaired listeners using muffs, plugs, and no protectors. The investigators found that normal-hearing subjects performed consistently better with plugs than unprotected by up to 2.5 dB, but consistently worse with muffs, where signal detection threshold levels increased up to 6 dB. Figure 18 from Lazarus (1983b), is based on the data of Lazarus et al. (1983). It shows the percentage of correctly identified signals as a function of signal level in noise at 97 dB(A), with the parameter being ear condition. One can see that performance is consistently improved by plugs, but degraded by muffs.

Hearing-impaired subjects, tested only with earplugs, performed increasingly poorly as their hearing threshold levels increased, but those with mild impairments performed about as well with earplugs as without them.

3.3.2 Detection of Unexpected and Difficult-to-Recognize Signals

Wilkins and Martin (1981) theorized that inattention could elevate the masked thresholds of warning sounds

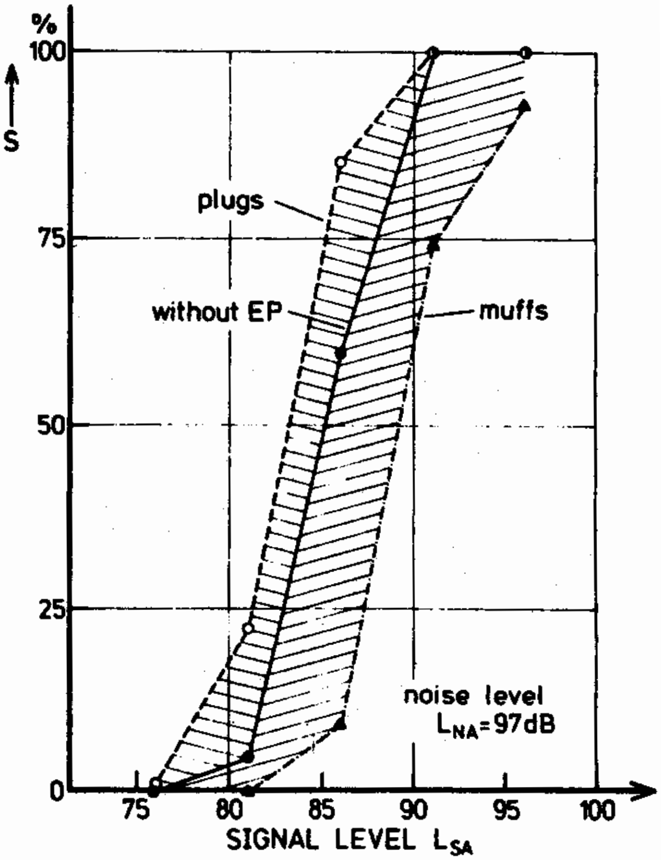

FIGURE 18. Percentage of correctly identified signals as a function of A-weighted signal level in a noise level of 97 dB(A). The parameter is ear condition: plugs, muffs, or unoccluded. (Lazarus, Wittman, Weissenberger, & Meissner, 1983. Reprinted by permission.)

when subjects were not expecting them, and the unexpected condition would be reflective of real-life situations. Consequently, they presented a wailing siren in a background of noise at 75 dB SPL at randomly intermittent intervals. Twelve normal-hearing subjects, with and without earmuffs, listened for the siren while they were engaged in a tracking task. Subjects received feedback on their performance on the task, and they were also given a monetary incentive for responding to the warning signal. The resulting detection levels were not significantly different from those when the signal was expected, and the addition of earmuffs did not change this finding. The authors do suggest, however, that although the signal was randomly intermittent, there was a "high degree of expectancy" among the subjects. Also the addition of incentives would further tend to minimize any differences.

In their next experiment, Wilkins and Martin (1984) tested the effects of hearing protector use in detecting unexpected signals among irrelevant yet meaningful stimuli. In other words, they combined the factors of attention demand (unexpected signals) and difficult signal recognition. For the background noise the investigators used broadband noise of 75 dB(C), upon which were superimposed four "workshop" sounds: grinder, engine, lathe, and drill noise. For warning sounds, they selected the wailing siren used in previous experiments, and the grinder noise. Sixteen subjects, engaged in a loading task, attempted to detect the warning sounds, which were presented with each of the four workshop sounds (overlaid on the noise background) at five signal-to-noise ratios. While the siren was reliably recognized at all five presentation levels, whether or not it was expected, the grinder was significantly more difficult to recognize when it was unexpected. With respect to the difference between the identification of expected and unexpected signals, the use of hearing protectors had no effect on siren recognition, and a small but nonsignificant effect on the recognition of the grinder noise.

Wilkins and Martin (1985) then attempted to ascertain whether the difference in warning signal effectiveness between the siren and the grinder could be related to spectral contrast to the background of noise and other signals. They point out that as an intentional alarm sound with a distinct tonality, the siren had a high contrast, both with the irrelevant workshop sounds and with the ambient noise, whereas the grinder had low contrast because of its noise-like character. In this experiment, they chose pure tones at 800, 2000, and 5000 Hz as irrelevant stimuli, superimposed on a background of broadband continuous noise as before. Subjects engaged in a loading task were instructed to identify target sounds consisting of the 2000-Hz tone and a narrow band of noise centered at 2000 Hz. The results indicated that the tone was less effective as a signal than the narrow band of noise, and both sounds were an average of about 6% less well perceived with hearing protectors than without. The authors conclude that the contrast with the irrelevant stimuli was greater for the narrow band of noise than for the tones, and that this factor is important in the recognition of warning sounds. They also conclude that hearing protectors will produce adverse effects in situations in which warning sounds are already difficult to perceive, either because of low contrast with environmental noise or because of competing irrelevant stimuli (or both). The addition of 6% failures in perception due to hearing protectors could be of marginal importance or it could be critical, depending on the circumstances. It does, however, argue against overprotection. The authors recommend replicating these studies using hearing-impaired subjects (Wilkins & Martin, 1982).

The experiments cited above by Wilkins and Martin were all conducted in the laboratory. Wilkins (1984), therefore, chose to study the effects of hearing protectors on the perception of warning sounds in the industrial environment. The setting was the press shop of a plant manufacturing air and oil filters for engines. The ambient noise environment was 85 to 95 dB(A), with impulses ranging from 105 to 115 dB(A). Wilkins selected as warning sounds the horn on a fork-lift truck and the clinking sound of metal pieces spilling out of a container. Three other machinery sounds served as competing irrelevant sounds. They were mixed with pink noise, and, with the signals, were recorded and delivered through loudspeakers. Signals were presented at five sound levels, in an irregular order, and in either a predictable or an unpredictable temporal pattern. Thirty workers performing their regular jobs were instructed to press a button when they heard the target warning sounds. Most subjects had some degree of hearing loss. All wore hearing protection in the afternoon (their own protectors, self-fitted), while most did not in the morning.

The results of Wilkins' study showed that neither target sound was completely effective as a warning signal, as even the highest signal level produced an overall response rate of only 85% (Wilkins, 1984). Although subjects with "substantial" hearing losses gave 18% fewer correct responses to the clinking sounds than did those with normal hearing or mild losses, they had no added difficulty hearing the horn. In comparison to the unoccluded condition, the use of hearing protectors produced an average of 9% fewer correct responses to the clinking sound, when the target sounds were unexpected. There were no significant differences in protector conditions when the target sounds were expected, nor were there in either category for the horn signal. The author notes that the decrement caused by hearing protectors (for the clinking sound in the unexpected mode) was greater than that observed in the laboratory, and attributes it to the reduction in loudness, acting in conjunction with the signal's reduced attention demand and the difficulties inherent in recognizing it among competing stimuli. A further explanation might lie in the spectral characteristics of the clinking sound, which the author does not discuss, and the fact that workers' hearing impairments may have interacted more adversely with the clinking sound's spectrum than with the spectrum of the forklift horn.

Although Wilkins' study has numerous strengths, it also has some significant weaknesses. As the author points out, the factory conditions "provided a high degree of realism" (Wilkins, 1984, p. 433). The subjects presented a range of hearing threshold levels, they worked at their own jobs, and wore various kinds of hearing protectors, which they fit themselves. The acoustics were those of an actual factory, and the stimuli were appropriate. There were many variables, however, that were partially or totally uncontrolled, which is not surprising in such circumstances. For ethical reasons, the investigator could not demand that all workers participate without protectors during certain portions of the experiment, so some workers wore protectors during the "unoccluded" periods. This would tend to reduce differences, so one could possibly expect a greater decrement due to protectors in reality. In addition, there were large variations in noise levels caused by the actual machinery, which would produce uncontrolled variations in the signal-to-noise ratios of the experimental conditions. There was also a variety of actual "irrelevant" stimuli, such as occasional real horns, and the possibility that subjects responded by observing the responses of other subjects. Thus, the results of this study should be interpreted with great caution. Nonetheless, it is the only one of its kind, it generally supports the findings of the laboratory studies that preceded it, and it should provide added incentive for the careful selection of warning signals and against the practice of over-protection.

3.3.3 Effects of Hearing Protectors on Localization

The ability to localize warning sounds can be very important to safety in a variety of occupations. Although the visual system is much more efficient at localization than the auditory system, the auditory modality has certain advantages. It provides spatial information for events that are remote from an individual's current visual orientation, and it also provides information on occurrences that may be blocked from the listener's line of sight (Perrott, 1987). Industrial workers have complained that hearing protectors, and in particular, earmuffs, reduce the ability to localize a sound source. W. G. Noble and his colleagues have investigated this problem in a series of laboratory experiments (Atherly & Noble, 1970; Noble, 1981; Noble & Russell, 1972; Russell & Noble, 1976).

In the first experiment, Atherly and Noble (1970) tested the effects of earmuffs on the ability to localize a 1000-Hz pure tone in the horizontal plane. Subjects were 15 men who had been working in a foundry and consequently had some degree of hearing loss. None had used hearing protectors before. Subjects' heads were not restrained, but they were instructed not to move. The 1000-Hz tones were presented at four sensation levels from six loudspeakers, arranged in a circle surrounding the subject. Analysis of the responses showed that the use of earmuffs significantly increased the number of contralateral (left-right) localization errors, from 13 unoccluded to 113 occluded for the group as a whole. The number of ipsilateral (front-back) errors increased, but was not significantly greater, with hearing protectors. However, the distribution of errors changed, with significantly more rearward than frontward errors. Because of a relatively low correlation between hearing threshold level and total errors, the investigators believed that hearing sensitivity was not an important factor. They concluded that ". . . ear-defenders need to be viewed with suspicion from the point of view of safety in industry" (Atherly & Noble, 1970, p. 265).

In an attempt to explain the effects found by Atherly and Noble, Noble and Russell (1972) tested two hypotheses. First, they theorized that the metal headband connecting the muffs might act as a conducting pathway and thus might interfere with the two ears' proper analysis of phase and intensity information. To test this hypothesis they modified the earmuffs by removing the headband and instructing subjects to hold the muffs against their ears. The second hypothesis was that the attenuation of earmuffs (or any protector) causes disruption of normal auditory contact with the environment by the attenuation of extraneous sound. To test this hypothesis, the authors used earplugs in addition to muffs. Fifteen normal-hearing subjects listened for a 1000-Hz pure tone and a band of white noise, both at a sensation level of 20 dB. Loudspeakers were arranged horizontally in a circle, as before.

The results of testing the first hypothesis again showed a significant increase in left-right errors, and this time front-rear errors as well, with the wearing of earmuffs. The muffs produced a greater decrement for the white noise than for the tone. There was no significant difference in the number of errors resulting from the modified or unmodified muffs and hence the first hypothesis was rejected. Testing the second hypothesis resulted in significantly better performance with plugs than with muffs, consequently disproving the hypothesis that the problem was due to attenuation alone. There was still, however, significantly poorer performance with plugs than unoccluded. Plugs did not produce significantly more left-right errors, but only front-rear errors, where once again responses favored the rear position. The decrement due to plugs was greater for the white noise than for the tone.

Russell and Noble (1976) further explored these questions by testing the effects of muffs and plugs on the ability to localize white noise from loudspeakers situated at 30 degrees, 60 degrees, 90 degrees, 120 degrees, and 150 degrees azimuths, all on the listener's left side. They examined decision certainty and error magnitude scores, as well as the frontward and rearward error directions. Once again, earmuffs produced a substantially greater decrement than earplugs. The results for plugs showed slightly (but not significantly) more total errors than in the unoccluded condition, but significantly more rearward errors. Earmuffs resulted in significantly more total errors than in the unoccluded condition, with approximately the same number of rearward errors and significantly more forward errors (in contrast to the earlier finding by Atherly & Noble, 1970). The investigators also found that responses with muffs were considerably more certain in the case of frontward errors. These findings are consistent with a rearward illusion for earplugs and a frontward illusion for earmuffs. The authors believe that they support an information transformation hypothesis for earplugs, suggesting that the effect of plugs is to attenuate high-frequency sounds in much the same manner as the pinna does with sounds coming from the rear. The result is a rearward illusion. The authors attempt to explain the greater decrements caused by earmuffs by an information reduction theory, in which the important information supplied by the pinna is missing entirely. It is interesting to note that the investigators chose glass-down earplugs, which have relatively poor attenuation in the low frequencies. If their plug had had a flatter spectrum, the "information transformation" might not have occurred at all. In fact, they suggest further research simulating positions in the horizontal plane by varying spectrum levels (Russell & Noble, 1976).

In a subsequent experiment, Noble (1981) tested the effects of earmuffs on both horizontal and vertical localization. By restricting head movements in one condition and allowing free movement of the head and torso in another, he was also able to study the added benefits of exploratory head movement. Ten loudspeakers were placed in the horizontal plane in a range of 180 degrees, and nine were placed vertically in a 160-degree range. Twenty-one subjects, wearing earmuffs and unoccluded, attempted to localize a ⅓-octave band centered at 1000 Hz at a level of 60 dB(A). The signal output was amplified by 25 dB in the occluded condition. Because subjects were to terminate each signal when they had decided on its location, the investigator could measure their response time.

The results showed that earmuffs degraded response accuracy in the horizontal plane and virtually destroyed it in the vertical plane. Free head movement improved the situation considerably, but mainly in the horizontal plane. In the horizontal plane, subjects' response accuracy was 95% in the unoccluded free-head-movement condition, 50% in the occluded free-head-movement condition, and 24% occluded and with the head restricted. Response times were 1.84 sec unoccluded, and 6.25 sec with earmuffs, both in the free-head-movement condition. Results for the vertical plane showed 72% response accuracy in the unoccluded free condition, 19% in the occluded free condition, and nearly random in the restricted-head occluded condition. Response times for the vertical plane were 4.7 sec in the open-ear free-head-movement condition, and 10.2 sec in the earmuffs free-head condition.

Noble concludes that the removal of the pinna by earmuffs has a definite adverse effect on horizontal plane localization and a radically disruptive effect on vertical plane localization. These effects are somewhat mitigated by free head movement, but only slightly so in the vertical plane. The investigator noted that subjects moved their heads and torsos considerably, sometimes out of the range of the video camera, and still the responses were only slightly better than chance. According to Noble, earmuff users, even when unrestrained, do not have a good grasp of vertical auditory space. This finding has implications for construction workers or anyone wearing earmuffs in a job requiring vigilance, especially in the up-and-down dimension (Noble, 1981).

Coleman and his colleagues have also noted that hearing protectors can have an adverse effect on the localization of desired sounds (Coleman et al., 1984). They point out that hearing protectors can have detrimental effects on localization in practical situations, and cite Talamo (1982) as showing this problem with tractor drivers. Coleman et al. raise questions as to the practical significance of this problem: what level of uncertainty is possible before safety and performance are impaired? They suggest that if the ability to localize needs improvement, then plugs are preferable to muffs, or an electronic circumaural earmuff could be developed, which is designed to maintain the sound information as it would be perceived in the unprotected condition (Coleman et al., 1984).

3.4 SPECIAL PROTECTORS

Over recent decades, certain hearing protectors have been developed with speech communication and signal detection in mind. These protectors may be classified as passive attenuators, active attenuators, and communication systems. Because the subject of communication systems constitutes an extensive topic on its own, it will not be covered in detail here. It should be sufficient to say that these devices can be extremely useful in protecting hearing and at the same time enhancing speech communication, provided that they possess certain features available with modern technology, such as noise-canceling microphones, wide frequency bandwidths, and fast-acting automatic gain control, as well as adequate noise attenuation.

3.4.1 Passive Attenuators

Forshaw and Cruchley (1982) report that Canadian gunners do not like to "don and doff" hearing protectors all the time, but prefer to cover their ears with their hands. Both hands, however, are not always free. For this kind of reason, level dependent or "nonlinear" hearing protectors have been developed that will allow speech communication at moderate intensities and provide increasing attenuation at high intensities. In the case of earplugs, a small hole in the plug allows frequencies below 1000 Hz to pass with little attenuation (Michael, 1965). At high sound levels the small orifice produces a turbulent flow, increasing impedance especially for high-frequency sounds. Because its greatest effectiveness is for high-frequency, high-level stimuli, this kind of protector was developed specifically for use with impulses from weapons (Mosko & Fletcher, 1971).

The Selectone-K plug, designed by Zwislocki, incorporates a two-stage filter. Figure 19, from Coles and Rice

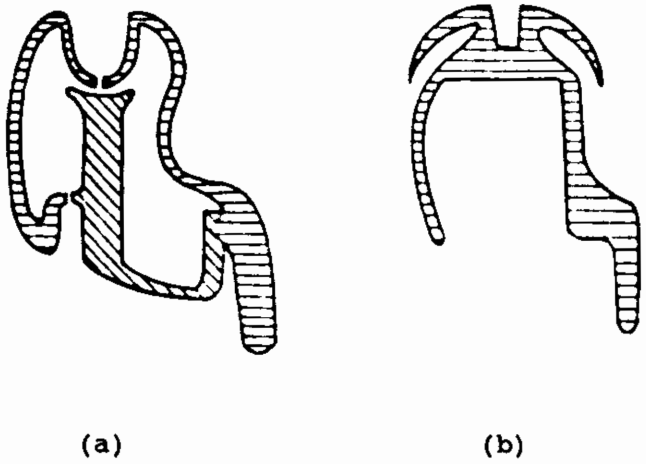

FIGURE 19. Schematic cross sections of (a) the Selectone-K, and (b) the V-51R earplugs. (Coles & Rice, 1965. Reprinted by permission.)

(1966), shows a schematic cross section of the Selectone-K earplug contrasted with the standard V-51R. Another popular design is a modification of the V-51R plug known as the Gundefender,[5] in which the core of the plug is removed and replaced by a small metal disk containing a hole of 0.0265 in. in diameter (Mosko & Fletcher, 1971). The attenuation of the Gundefender is negligible under about 110 dB, above which it increases, with considerably greater attenuation above 140 dB (Forrest, 1981). Figure 20 (from Forrest, 1971) shows the Gundefender's attenuation growth as a function of peak sound pressure level of 140 dB and above. Measurements were made at the canal entrance and near the tympanic membrane of a cadaver ear.

These types of protectors may present certain problems. Forshaw and Cruchley (1982) warn against using this type of hearing protector in high-level steady-state noise because of its poor low and mid-frequency attenuation. They report that at 850 Hz its attenuation is −8 dB. The orifice also acts as a resonator, and actually amplifies certain frequencies. Michael (1965) states that the metal parts can sometimes injure the ear canal, but he does not give the mechanism for such injuries. Coles and Rice (1966) found that Selectone-K users were dissatisfied with the plugs because they were less comfortable and more difficult to size, fit, and use than the standard V-51R. They also reported that the Selectone-K's central core would sometimes become lost, and that as many as 60% of the plugs fell out during a field experiment involving their use (Coles & Rice, 1966).

There have been some attempts to evaluate the effects of these nonlinear protectors on the intelligibility of speech. Michael (1965) reports substantially higher speech recognition scores for protectors with acoustical filters than for those without filters at speech levels of approximately 45 to 70 dB SPL in a quiet background. In masking noise at 88 dB SPL, performance with the two protectors was much the same for speech levels of 70 to 85 dB SPL. Mosko and Fletcher (1971) found that in moderate noise levels (70 dB SPL) individuals wearing the Gundefender recognized speech better than when using the V-51R, and almost as well as in the unoccluded condition. In high noise levels (100 dB SPL) individuals gave the same scores with the V-51R and in the unoccluded condition, but significantly poorer scores with the Gundefender.

In a laboratory and field investigation of the V-51R and Selectone-K earplugs, Coles and Rice (1966) tested the effects of these protectors on speech recognition in various conditions. In the laboratory, 12 normal-hearing subjects listened to PB monosyllables in three ear conditions (unoccluded, V-51R, and Selectone-K), at sensation levels of 35 and 70 dB, in quiet, and at the 35-dB sensation level at a speech-to-noise ratio of 2 dB. In the field experiment, 12 Royal Marines responded to shouted orders in quiet and with impulse noise (machine gun bursts) in the background at peak sound pressure levels of 156 to 161 dB. Results of the laboratory study indicated that in quiet, the Selectone-K plug necessitates a speech level about 4 dB lower than the V-51R for equivalent intelligibility, although this speech level was about 15 dB higher than that required in the unoccluded condition. In noise, performance with the Selectone-K was not as good as with the V-51R. At optimal listening levels, meaning speech reception threshold plus 35 or plus 70 dB, there was no significant difference in speech recognition scores among the three ear conditions. Results of the field experiment, however, were not quite so satisfactory. In the quiet background, the percentage of orders heard correctly were 84% unprotected, 73% Selectone-K, and 68% V-51R. Estimated percentage of orders heard correctly in the noise environment were only 40% unprotected, 34% Selectone-K, and 16% V-51R. Coles and Rice conclude that the Selectone-K allows generally better communication than the V-51R plug, but that it is less comfortable and more difficult to fit and use.

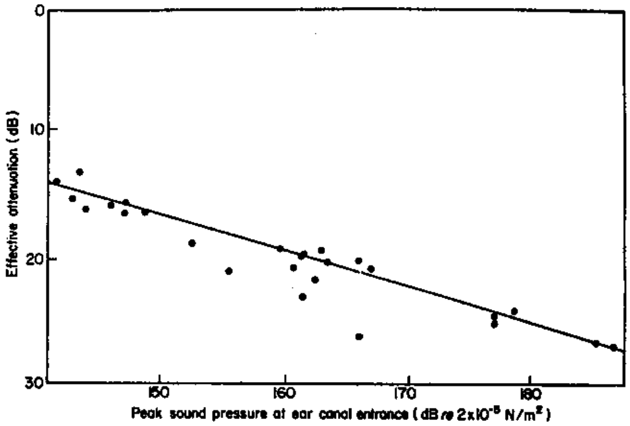

FIGURE 20. Impulse attenuation from the "Gundefender" earplug as a function of peak SPL at the ear canal entrance. (Forrest, 1971. Reprinted by permission.)

Recent developments in the design of a passive, nonlinear earmuff provides grounds for optimism. Allen and Berger (1990) report on the design and refinement of a level-dependent muff using a valve system to effect low levels of attenuation in low noise levels, with significant amounts of attenuation in impulsive noise conditions. The resulting earmuff is marketed by the Cabot Corporation as the "Ultra 9000." A bank of small orifices in a tuned acoustical duct allow speech and other moderate-level sounds to be heard, but impulses and other high-level sounds above about 120 dB create a turbulent airflow, impeding the passage of these sounds. The addition of an unusually flat attenuation spectrum affords greater speech recognition than is available in most contemporary hearing protectors. Figure 21, from Berger (1990), shows the attenuation of the Ultra 9000 earmuff contrasted to that of a conventional muff.

Subjective evaluations of the Ultra 9000 earmuff were obtained by Stokes et al. (1991) from a population of 139 police officers. Results showed that a majority of the subjects preferred the nonlinear muff to a look-alike version, in terms of comfort, perceived hearing protection, and the ability to communicate while wearing the device.

Another promising development is the ER-15 earplug. This plug provides a uniform attenuation of approximately

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[5] Also called the Gunfender (see Forshaw & Cruchley, 1982).

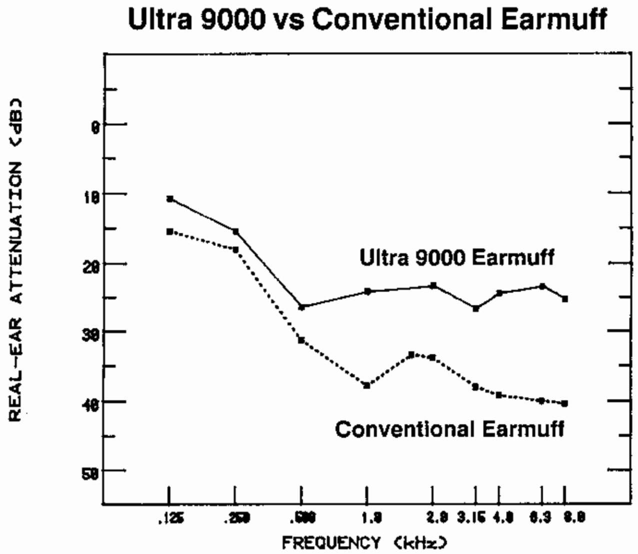

FIGURE 21. Attenuation as a function of frequency of the Ultra 9000 earmuff compared to an example of a conventional earmuff. (Berger, 1990. Reprinted by permission.)

15 dB throughout nearly the entire frequency range, as shown in Figure 22, from Berger (1990). According to Killion et al. (1988), the acoustics of the ER-15 plug were developed to mirror the natural response of the open ear, while providing some amount of attenuation. It has become known as the "musician's earplug" because of its popularity among musicians, who require spectral "fidelity." It could also be quite useful for factory workers who must receive a certain amount of attenuation, but who need to maintain the ability to hear speech and warning sounds. Killion and his coauthors, however, report that the ER-15's noise reduction rating (NRR)[6] is only approximately 5 to 8 dB, so it is not appropriate for all industrial uses or for persons who fire weapons (Killion et al., 1988). Another drawback is that each plug must be custom molded to the user's ear, which adds considerably to the expense.

3.4.2 Active Attenuators

Two types of earmuffs can be classified as active attenuators. One uses noise cancellation techniques to achieve attenuation; the other uses an amplifier to permit the passage of low and moderate-level sound, maintaining a constant level at the ear. It then acts as a passive attenuator at high levels (Maxwell et al., 1984).

An example of the noise-cancelling system has been described by Jones and Smith (1981). It consists of an open-backed headphone, which produces a sound field at the ear minus the cancelled components, a dual-channel cancellation module, and a synchronizing system to the noise source. It provides noise cancellation, especially in the low frequencies, of up to 50 dB, and passive protection in the higher frequencies. Jones and Smith describe their system as lightweight, economical, and potentially useful against noise produced by helicopters, air or gas-operated hand tools, vehicle engines, or in engine or control rooms where noise is concentrated in certain frequency regions. They mention that this kind of protector can restore direct speech communication, but they do not elaborate on the speech communication advantages.

Pilots of the experimental aircraft Voyager used another noise-cancelling device in their circumnavigation of the globe, allowing them to avoid the permanent hearing loss that their flight surgeon had predicted (Gauger & Sapiejewski, 1987). This system also provides considerable added protection in the low frequencies, producing a relatively flat attenuation that is desirable for speech communication. The system has been jointly developed by the Bose Corporation and the U.S. Air Force, where research on active attenuators continues (McKinley, 1987).

According to Nixon and his colleagues, as of 1989 at least seven different companies have working models of active noise reduction headsets using noise cancellation technology (Nixon et al., 1991). The Air Force has examined several of these models, measuring sound attenuation and speech communication effectiveness, among other parameters. Nixon and his coworkers measured attenuation and speech intelligibility in high levels of pink noise. They found considerable variability among headsets, with active attenuation levels (the difference between passive and total attenuation) of up to 22 dB in the lowest frequencies, but a loss of attenuation between 500 and 1500 Hz in several models, and virtually no active attenuation above 1000 Hz.

Speech intelligibility for three of the noise-cancelling de-

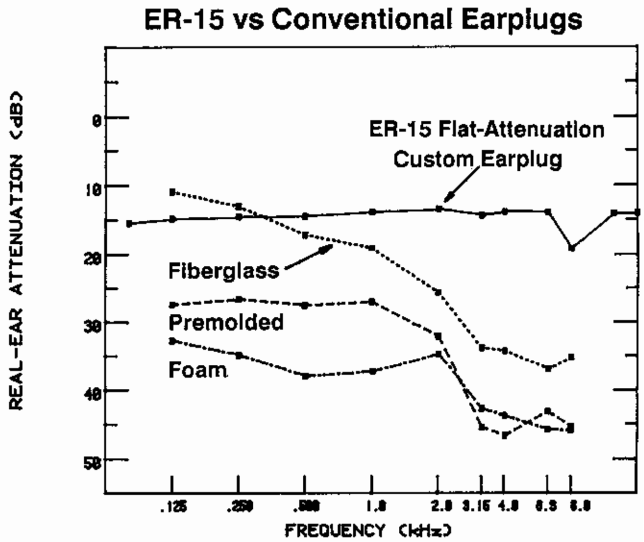

FIGURE 22. Attenuation as a function of frequency for the ER-15 earplug compared to examples of the attenuation data from three conventional earplugs. (Berger, 1990. Reprinted by permission.)

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[6] The NRR is a laboratory-based statistic representing the mean attenuation minus two standard deviations in a population of trained listeners. Although this rating currently is required to be published on the ear protector's label, it usually reflects an overestimate of the attenuation actually realized in field use of hearing protectors.

vices was assessed using the Modified Rhyme Test presented in four levels of pink noise from 75 to 115 dB (Nixon et al., 1991). Although the results were not dramatically better in the noise-canceling devices, the best results were achieved in the 115-dB noise condition, where two of the devices provided up to 10 percentage points of intelligibility over the passive attenuators. Tests using the Articulation Index showed that any improvements in noise cancellation around the 1000-Hz frequency would most likely produce substantial gains in intelligibility. Subjects did report greatly increased comfort in the active mode, which was undoubtedly due to the attenuation of low-frequency noise. Thus, the use of noise-canceling systems should provide reductions in noise-induced hearing loss and fatigue as beneficial side effects.

The other type of active attenuator, that which uses an amplifier for low and moderate sound levels, has been described by Maxwell et al. (1987). Landing Signal Officers on aircraft carriers exposed to transient (1–2 sec) noise levels at 120 dB(A) have expressed reluctance to wear hearing protection because of the need to communicate with pilots through a telephone handset. Consequently, the authors evaluated four active attenuation devices for certain physical parameters, and two of the four for speech intelligibility. Using the Tri-Word Modified Rhyme Test in four levels of Gaussian noise and at two speech-to-noise ratios, they found that in the more favorable speech-to-noise ratio (+4 dB), speech recognition was always better in the unprotected condition, but that one device produced scores that were nearly as good in the highest noise level (90 dB SPL). In the more difficult speech-to-noise ratio (0 dB) the same device produced better speech recognition scores than the unprotected condition in the lowest (60 dB) and highest (90 dB) noise levels, but not in the intermediate noise levels. Individuals wearing the other device performed consistently more poorly than in the unoccluded condition, particularly in the higher noise levels. Maxwell et al. also found that although attenuation in the passive mode was generally good (about 32–35 dB), two of the three commercially available devices fell considerably short of the manufacturer's specifications and of the authors' stated criteria for these kinds of protectors. The level at which the devices stopped amplifying and acted as passive protectors was considerably lower than it should have been, and there were no plateaus produced by selective amplification at levels around 85 dB. One of the commercially available devices, as well as the Navy's own prototype, came quite close to the target criteria, but these two devices were not tested for speech intelligibility. These results suggest that this type of active hearing protector can be of some benefit to speech communication, but that these protectors need to be evaluated further before they are used in situations in which speech communication is critical.

3.5 SUMMARY

Many industrial workers and soldiers dislike wearing hearing protectors, claiming that they interfere with communication and the perception of warning signals. Theoretically, hearing protectors should actually improve communication in high noise levels. While this is often the case, both laboratory and field research points to numerous conditions in which protectors provide no improvement or have an adverse effect.

3.5.1 Effects on Speech Communication

Hearing protectors attenuate the noise and the signal by equal amounts within a given frequency range, reducing both to a level at which there is less distortion, and providing better listening conditions. These improvements can be experienced when the noise level is above 80 to 90 dB, the listener has normal hearing, and the talker is not wearing protectors. Even when these conditions are met, the crossover level from disadvantage to advantage can be somewhat higher (for example, over 100 dB), depending on speech-to-noise ratio.

Hearing protectors usually have an adverse effect on speech recognition when the listener is hearing impaired. This appears to be true of listeners with average hearing threshold levels greater than 30 dB at 2000, 3000, and 4000 Hz. The most plausible mechanism for this occurrence is the reduction of certain signals below the level of audibility, eliminating important speech cues, particularly those in the high frequencies.

In addition to hearing loss, other conditions interact with hearing protectors to affect speech recognition. Visual cues aid speech recognition, with and without protection, and may even decrease any disadvantages due to the wearing of protectors. The talker's ear condition also affects the listener's ability to understand speech. Due to the occlusion effect, the talker's voice sounds louder, and hence the vocal output is 2 to 4 dB lower. The result is a decrease in speech recognition by the listener, which more than offsets any gains that would have occurred from the use of protectors, had only the listener worn them. Talkers with hearing protectors also appear to articulate more rapidly and pause more briefly between words. The poorest performance occurs when both talkers and listeners wear hearing protectors, which most closely resembles real-life conditions. This situation can be mitigated somewhat through verbal feedback. It also seems that earmuffs have a greater adverse effect on speech recognition than earplugs, although this difference may be due to the spectral properties of the devices tested rather than any other physical characteristics peculiar to earmuffs.

3.5.2 Effects on Warning Signals

The same kinds of theoretical considerations that apply to speech recognition hold for the detection of warning signals while wearing hearing protection. The attenuation of high noise and signal levels facilitates the perception of signals by taking them out of the range of distortion. This is generally borne out by the research, using normal-hearing listeners, relatively high noise and signal levels, and simple detection paradigms. The crossover level between disadvantage and advantage of hearing protectors appears to be about the same as it is for speech recognition: about 80 to 90 dB.

Hearing protection can degrade the ability to detect warning sounds under various conditions. Protectors are more likely to be responsible for adverse effects when the signal is unexpected, and especially when it is embedded among other similar but irrelevant stimuli. Not unexpectedly, hearing protection appears to degrade signal detection by people with impaired hearing, although the research in this area is not as extensive as in the area of speech recognition. The only industrial field study (Wilkins, 1984) is plagued by methodological problems, but it does tend to support the laboratory results, in that subjects wearing hearing protectors (most of whom had some degree of noise-induced hearing loss) gave fewer correct responses to a difficult-to-recognize target sound than when they listened in the unprotected mode.

Once again, research has indicated that earmuffs cause a greater decrement than earplugs. One study found a consistent enhancement of signal detection by plugs, but a consistently adverse effect on the part of muffs (Lazarus et al., 1983b).

That both plugs and muffs adversely affect the ability to localize acoustic signals is quite clear, and this is especially true of muffs. Earplugs produce mainly ipsilateral (front-back) effects, with significantly more rearward errors, indicating a rearward illusion of the sound source. Earmuffs are the cause of contralateral (left-right) localization errors, as well as ipsilateral errors, with an apparent tendency toward a frontward illusion of the sound source. Earmuffs drastically impede localization in the vertical plane, even with free head movement.

These findings have serious implications for safety in noisy working conditions. Warning signals not only need to be detected and recognized, but their locations must be determined, so that individuals may either approach and remedy the situation or get out of the way.

3.5.3 Special Protectors

Various kinds of special protectors have been developed to enhance speech communication during noise exposure and to permit it during quiet intervals.

Special passive attenuators can improve communication with protectors during the quiet intervals between noise bursts, so that the wearers are not inclined to take them on and off so frequently. Passive attenuators include modifications of the V-51R plug, such as the Selectone-K and the Gundefender, and a new nonlinear earmuff, the Ultra 9000. These protectors give relatively little attenuation at moderate noise levels (even acting as amplifiers at times), but increasingly greater attenuation at levels over about 110 to 120 dB. Because of this they are mainly useful in impulsive noise conditions, such as firing ranges. Speech recognition experiments with nonlinear plugs indicate that they can enhance performance in moderate speech levels (around 70 to 88 dB), and above these levels produce about the same speech recognition as a standard earplug. It appears, however, that the comfort and practicality of some of these devices leaves something to be desired. These practical problems do not apply to the nonlinear muffs, however, or to the recently developed ER-15 earplug, whose flat attenuation spectra are more conducive to improved speech communication and warning signal perception.

Through modern technology, special protectors also can enhance communication in certain noisy conditions and permit communication in levels of noise when it would otherwise be impossible. These protectors use active attenuation techniques. One type uses noise cancellation mechanisms. The other uses an amplifier, which maintains a constant signal level at the ear, cutting off at levels above 85 to 90 dB, at which point the device acts as a passive attenuator. Speech intelligibility testing with both types of protector indicates performance advantages under some conditions, but not others. Physical measurements indicate that these products do not always conform to the manufacturer's specifications, so benefits to speech communication cannot necessarily be assumed. It appears that both types of device are still in the developmental stage.

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Chapter 4

The Effects of Noise on Task Performance

Noisy operations are ubiquitous in industry and in the military, and the personnel who work close to the noise sources must continue to perform their jobs effectively, despite the bang, whine, roar, or thunder nearby. Today, there is considerable evidence that noise can disrupt task performance, even when communication is unnecessary or, at least, not problematical. Adverse effects can occur even when personnel are wearing hearing protectors. But there is also evidence that noise sometimes has little or no effect on job performance, and in some cases actually appears to enhance it. This section will review and analyze the literature in this area for the purpose of obtaining greater clarity with respect to the types of noise, jobs, and environments that produce specific effects. Special emphasis is given to noise conditions, jobs, and effects that are characteristic of military operations, but many of these operations can be found in civilian work settings as well.

The effect of noise on task performance is the subject of voluminous literature. Literally hundreds of studies have been conducted, examining the problem from a great variety of approaches. Because it is beyond the scope of this section to explore thoroughly each of these approaches, a broad overview of the problem will be provided, citing examples of the relevant research. This process has been aided by a number of fine reviews (Broadbent, 1971, 1979, 1983; A. Cohen, 1977; S. Cohen & Weinstein, 1981; Glass & Singer, 1972; Gulian, 1973; Jones, 1983; Loeb, 1980; Loeb, 1986) to which the reader may turn for additional information.

One particular area will be examined in somewhat greater depth. The effects of noise on sensory and motor function have been selected for a relatively more detailed review because of their relevance to the success of military operations. Other effects, such as those on cognitive processes and social interaction, are also extremely important and merit scrutiny in subsequent work. But it appeared that sensory and motor effects would provide a good starting point because any reduction in the ability of military personnel to shoot accurately, drive vehicles, fly planes and helicopters, and exit effectively from noisy conveyances could have serious consequences. Performance decrements could potentially result in minor inconveniences, combat disadvantages, mission failures, accidents, injuries, and even loss of life, depending on the nature and magnitude of the decrement and the context in which it occurred. Likewise, impaired performance can pose a safety hazard in industrial or construction settings when high noise levels accompany dangerous jobs.

The effects of noise on performance have generated considerable controversy in the scientific community. Numerous studies have shown significant performance decrements, whereas many others have shown small effects that are not statistically significant. Other experiments show no effect at all, and quite a few indicate that noise can actually enhance performance. According to D. E. Broadbent, one of the most prolific researchers in this area:

> The topic arouses strong emotions, both from those who assume that any noise will impair any human function and from those who deny that it does anything beyond making it harder to hear. The first group sees any statement that a given function is as efficient in noise as in quiet as an argument for keeping noise levels high and therefore as objectionable; the second group tends to suppose that it is a waste of time to examine the accidents or errors of workers in a factory where there are no complaints. Both these extreme views are false. The effects of noise on performance are definite, but depend very much upon the task which is being performed (Broadbent, 1979, p. 17-1).

Sometimes an author's approach betrays a bias. For example, Stevens (1972) discusses both noise and "glare" pollution, wondering "why it is that the so-called disaster lobby, which propounds a message of environmental doom, agitates against noise but seldom against glare." He continues to express skepticism by saying: "Although I do not like noise and glare, it seems to me that some of their alleged debilitating effects have been grossly exaggerated. Those leading the charge against noise pollution sometimes subject us to another kind of pollution, the pollution of intemperate protest, the pollution of imagined trauma" (Stevens, 1972, p. 36). When the author proceeds to discuss the results of a series of studies conducted by himself and his colleagues, showing little or no effects from high levels of noise, it would not be surprising if he elicited the same kind of skepticism in his readers.

Studies of the effects of noise on performance also seem to be particularly prone to more than one interpretation. The theoretical bases for these effects (or lack of effects) are very complex, subject to controversy, and have evolved considerably over recent years. In addition (or perhaps consequently), some researchers will consider effects that are not statistically significant nonetheless important, while others will cite the same study as showing no effects.

Broadbent (1979) discusses the various problems that characterize these kinds of studies. Industrial studies suffer from the lack of control of other conditions and the tendency for workers' performance to improve with any change in working conditions (the "Hawthorne effect"). Problems occurring in laboratory studies include intersubject and intrasubject variability that is due to chance, and variability that is due to uncontrolled factors, such as fatigue. The control and specification of the noise stimulus differs widely (Broadbent, 1979). As an example of the disparity here, one study refers to a level of 50 dB, generated conveniently by experimental apparatus, as "noise" (Frith, 1967), while another refers to synthetic airplane noise at 90 dB as "quiet" (Stevens, 1972). In addition, descriptions of spectral and temporal characteristics are often omitted, especially in some of the older studies.

Other factors can also contribute to difficulties in interpreting the results of studies on noise and performance. First, there is a multiplicity of tasks, which will be discussed subsequently in greater detail, but also the subject's biological and psychological state can have an effect. Important biological variables include time of day, state of arousal, and perhaps gender (Broadbent, 1983; Loeb, Baker, & Holding, 1983). Psychological variables include motivation, attitude, "neuroticism" index, familiarity with the noise and the task, and coping strategies (Gulian, 1973; Broadbent, 1983).

One other area of complexity is the role of hearing protectors. Quite a few of the studies of high-level noise exposure have employed hearing protectors. The investigators have assumed attenuations of about 25 to 40 dB (Harris & von Gierke, 1971; Nixon, Harris, & von Gierke, 1966). In interpreting these studies, readers must first be aware that both the noise level and the spectrum will be considerably modified upon arrival at the cochlea. Also, the intersubject variability is likely to be increased because protectors will provide somewhat different amounts of attenuation among different wearers, especially if subjects insert their own earplugs.

Popular opinion holds that we need not be overly concerned about high levels of noise exposure, because these days all personnel who work in these environments wear hearing protection (Harris, 1973). This is a dangerous assumption. Simple observation, as well as methodical survey (Walden, Prosek, & Worthington, 1975), reveals that soldiers and other personnel exposed to high noise levels very often do not wear hearing protection. When they do, the fitting and wearing procedures seldom match the effectiveness of those used in the laboratory (Berger, 1986), so that attenuation of 25 to 40 dB would be quite rare. Studies of the field attenuation of hearing protectors indicate that the mean attenuation is nearly one third of that realized in the laboratory, and the standard deviation is three times larger (Berger, 1983). These facts must be considered when reviewing the research on the effects of noise on performance and attempting to apply it to real-life conditions.

There are, therefore, many difficulties in interpreting the literature on noise and performance, and others in applying it to the real world. Despite these difficulties, the sheer quantity of the data, as well as the quality of many of these studies, allows us to draw certain conclusions. As Broadbent and many others have pointed out, there are definite effects of noise on task performance, but the situation is very complex, and the effects depend on a number of variables besides just the presence or absence of noise.

4.1 MECHANISMS

Some of the early investigations of the effects of high-level noise exposure took place under military auspices in the early 1950s. These studies were published together in what is known as the BENOX Report, short for Biological Effects of Noise Exploratory (Davis, 1953). One of these investigators, A. A. Ward (1953), concluded that high levels of noise stimulate, via the auditory nerve, the brain's reticular activating system, producing a state of wakefulness in the cerebral cortex and generally arousing the nervous system. He noted that "there are rich collaterals to this region [the reticular formation] from the acoustic pathways, and there is presumptive evidence that the labyrinthine component of the eighth nerve plays an even greater role in maintaining the normal activity of this region" (Ward, 1953, p. 74). Preliminary animal experimentation indicated a definite increase in electrical activity in the reticular formation in response to an 880-Hz tone at 137 dB, and in a human subject EEG alpha rhythms changed dramatically at that sound level, although the effects tended to decrease with repeated stimulation. Ward and his colleagues also found an increase in deep tendon reflexes at levels of about 134–136 dB, which Ward suggests could result in muscular weakness. He also suggests that since stimulation of the reticular activating system can precipitate epilepsy, individuals with this condition should avoid exposure to intense noise. (This caveat does not appear elsewhere in the literature cited in this report.)

In his review of the extra-auditory effects of noise, A. Cohen (1977) reaffirms the role of the eighth cranial nerve in stimulating the reticular activating system. Then, from this point, neural impulses "can spread diffusely into higher cortical areas that control alertness, cognition, and coordinated perceptual-motor behavior, i.e., task performance. At the same time the reticular formation can convey impulses to centers of the autonomic nervous system, thus triggering glandular, cardiovascular, gastrointestinal and musculoskeletal changes as part of a generalized somatic response to the excitation" (A. Cohen, 1977, p. 31). Figure 23 displays a suggested model of this mechanism adapted by Cohen (1977) from the work of Grandjean (1969) and Kryter (1970).

4.2 SENSORY AND MOTOR EFFECTS

Because of the interconnection of neural pathways in the central nervous system, the existence of intersensory and sensorimotor effects from sound stimulation would not be surprising. Studies of this area can be roughly categorized as visual, vestibular, and motor effects. Although many of these effects are small or even insignificant, some would be substantial enough to produce performance decrements in real-life conditions.

A good example of some of the more dramatic effects is provided by a series of experiments by Mohr, Cole, Guild, and von Gierke (1965) in which subjects listened to very high levels of low-frequency noise and infrasound in the protected or unprotected modes. Two-minute durations as high as 140 to 155 dB produced a range of effects, from mild discomfort to severe pressure sensations, nausea, gagging, and giddiness. Effects also included blurred vision and visual field distortions in some exposure conditions. The nature and degree of all effects was dependent upon both sound level and frequency, with the most severe effects occurring in the audible frequency range (as opposed

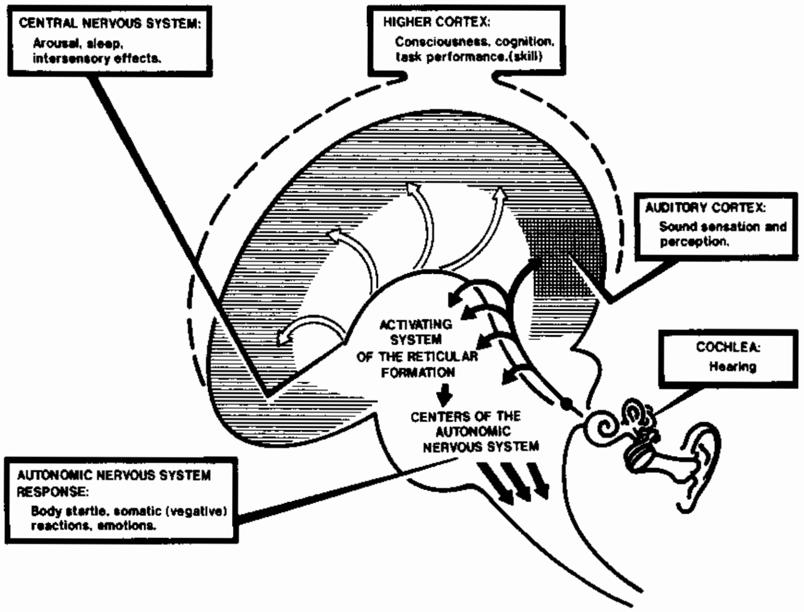

FIGURE 23. Hypothetical model of the extra-auditory effects of noise. (Cohen, 1977. Reprinted by permission. Adapted from Grandjean, 1969, and Kryter, 1970.)

to infrasound), at levels above about 145 dB. The investigators found no temporary threshold shift (TTS) among their subjects, and the use of hearing protectors greatly alleviated the adverse effects (Mohr et al., 1965).

4.2.1 Effects on Vision

Some research has shown that minimum visibility thresholds for light are unaffected by noise levels as high as 140 dB (e.g., Coleman & Krauskopf, 1956, cited in Cohen, 1977). Jones, Loeb, and Cohen (1977) tested subjects in both impact noise at 135 dB (peak SPL) and continuous noise at 110 dB(A). Although pupil size increased with noise stimulation, visual acuity was not affected. In fact, the continuous noise exposure produced a slight improvement in acuity at first, which then adapted to pre-exposure levels. Pupil size also appeared to adapt with continued exposure.

In a review of some 500 Soviet studies on sensory interactions, London (1954) found a number of studies showing noise-induced decrements in peripheral visual sensitivity. Soviet research tended to show increases in central sensitivity to white light, but differential sensitivity to colored light, depending on the wavelength tested. The author admits that much of the Soviet work "adheres to standards of execution, reportage, and interpretation that would be quite unacceptable to the Western researcher . . .", but that Western work on sensory interaction has been "scattered and desultory, whereas in the Soviet Union the subject has been given systematic and sustained attention" (London, 1954, p. 531).

Numerous other studies have supported differential sensitivity to colored light under noise stimulation. Kravkov (1936) found that a 2100–Hz tone at 100 dB improved sensitivity for green-blue light and decreased sensitivity for orange-red. Letourneau and Zeidel (1971) replicated Kravkov's earlier work using more subjects and experimental conditions. They used a 1000–Hz tone at 0, 50, 70, and 90 dB (audiometric hearing threshold level), and found that acoustic stimulation lowered the threshold for green and white light, without regard to sound level, and that the threshold for red light was elevated significantly in high sound levels, but not in the lower levels. In a related experiment, Yakovlev (1938) found that in noise conditions, the limits of visual fields change according to color, with green and blue fields expanding, orange-red contracting, and red exhibiting no change. Those experiments may have implications for the perception of red or orange-red signals, and appear to be worthy of further exploration.

Noise exposure may also affect visual discrimination abilities. In his discussion of Soviet research, London (1954) noted two studies showing that noise causes a decrease in differential sensitivity to brightness on an already bright field. Broussard, Walker, and Roberts (1952) also found thresholds for brightness discrimination slightly less acute in 90–dB noise levels, and greater response times for faint light differences (cited in Cohen, 1977). Harris (1968) exposed subjects to broadband noise levels of 70 dB (control), 120, 130, and 140 dB SPL. Subjects wore either earplugs in both ears (symmetrical exposure) or plugs in both ears plus a muff over the right ear (asymmetrical exposure). The results of a visual discrimination task showed decrements for asymmetrical exposure, especially at the 130 and 140 dB levels, but not for the symmetrical exposures. The decrements took the form of a greater number of errors, not slower response times.

Another interesting visual research area is the effect of noise on critical flicker fusion (CFF), the frequency at which flickering light appears to be in a steady state. Certain experiments have been cited as showing beneficial effects. For example, Frith (1967) found improvements with "noise" exposure, presumably due to increases in the subjects' state of arousal. Subjects categorized as extroverts showed more improvement than those classified as introverts. A closer look at the experimental procedures reveals that the "noise" was, in fact, an ambient room level of about 50 dB SPL, and "quiet" was produced by hearing protectors with an estimated attenuation of 30 dB. While the 50-dB level might be considered "sound," it could hardly be considered "noise."

Other studies indicate varying effects of noise on CFF. London (1954) reports Soviet research as showing that CFF for green light is reduced, while CFF for orange-red light is raised. Few details of experimental procedures are given. A study by Maier, Bevan, and Behar (1961) gave almost opposite results, with noise reducing the CFF for orange-red stimuli, increasing the CFF for blue stimuli, and producing no change for green flashes. The effect was "small and complex" (changes of 2% to 4%). "Noise" stimuli consisted of pure tones at relatively low levels: 40 and 80 phons, which, once again, should be considered sound rather than noise.

The fact that some investigations of noise and vision have produced beneficial effects whereas others have produced decrements may not be so mysterious. London (1954) refers to the "rule of inversion," which states that stimuli of weak intensity produce one result, whereas the same stimuli when strong, produce the opposite result. He quotes Kravkov as saying that this effect does not always occur, but Letourneau (1972) also offers it as a possible explanation, noting many examples of it in the literature on sensory effects.

McCroskey (1957) studied CFFs of 10 to 62 Hz (presumably for white light) in 40 subjects during exposure to white noise at 94 dB SPL. Subjects showed significantly lower CFF during noise exposure, with no adaptation apparent. In a follow-up experiment, McCroskey (1958) examined the effects of several noise levels and longer exposures on CFF in 72 subjects, divided into groups of 9. White noise levels from 85 to 115 dB SPL produced significantly lower CFFs than during the quiet condition, regardless of the noise level. Longer durations (approximately 19 min) produced additional decrements at the 85-dB and 115-dB exposure levels, but not at the two interim levels of 95-dB and 105 dB. The author is unable to explain the differential effects. He suggests that these decrements may be problematical when individuals must make careful judgments among visual stimuli (McCroskey, 1957, 1958).

Other effects of noise on vision have been cited in the literature. In their investigations, Stevens and his colleagues included the effects of high levels of noise on vision (Stevens, 1972). They found a slight but not statistically significant decrement in visual accommodation (near to far and far to near). Because the same effects occurred when subjects used earplugs, they concluded that the mechanism was other than auditory. However, because subjects were exposed to continuous levels of noise at 115 dB, it is possible that the attenuation of hearing protectors was not sufficient to create a "non-noise" condition. The investigators found a decrement in speed of eye movement in 1 out of 4 subjects, but again the effect was not statistically significant. Also, the threshold for dark adaptation was slightly, but not significantly, higher in intense noise (Stevens, 1972). The fact that these investigators used a very small and select subject population (an N of only 4 or 5), and a "quiet" level of 90 dB, is likely to have had considerable influence on tests of statistical significance.

One of the most interesting and well-researched areas is the effects of noise on visual field perception. According to Ades (1953), some of the early BENOX investigators found a slight, apparent shift of visual field usually toward, but in one instance away from, the exposed ear when the opposite ear was occluded with an earplug. This occurred for 1000- to 1500-Hz sound stimuli at a level of about 135 dB. Benko (1962) reported a concentric narrowing of the visual field resulting from exposures of 110 to 124 dB, and Chandler (1961) found that vertical lines were perceived to be tilted away from the primary source of sound stimulation when the sound level differed for the two ears (both studies cited in A. Cohen, 1977).

Parker and his colleagues performed a series of experiments on the effects of audible sound and infrasound on animals and humans (Parker, Gulledge, Perez, & Poston, 1968; Parker, Ritz, Tubbs, & Wood, 1976; Parker, Tubbs, & Littlefield, 1978; Parker, von Gierke, & Reschke, 1968). The investigators noted that other researchers had found shifts in visual field resulting from very high sound levels, namely 142 to 169 dB (Reschke, Homick, Landreth, & Parker, 1975, cited in Parker et al., 1976). Rapid-onset tone bursts had produced lateral shifts of visual field, and slow-onset bursts produced a tilting or rotation effect. Apparently, the 800- to 900-Hz range produced the maximum response (Reschke et al., 1975). Parker et al. (1976) found apparent shifts in visual field in approximately half of their subjects as a result of acoustic stimulation at much lower levels—120 to 125 dB. They found that the 500- to 800-Hz region resulted in the largest response, and that slow signal repetition rates (1/sec) produced the greatest perception of motion.

In a follow-up investigation, Parker and co-workers studied visual field shifts in 133 subjects as a function of stimulus frequency, repetition rate, and onset/offset time (Parker et al., 1978). Tone bursts at 100, 200, 500, 1000, 2000, and 5000 Hz were presented in six stimulus trains, 10 bursts in each train, at a sound level held constant at 125 dB. The stimulus was varied according to repetition rate, 0.5/sec to 4.8/sec, and onset/offset time 0.2 to 25 msec. Subjects were asked to observe a black cross on a white background, and to report any changes. Those who reported target motion as a result of stimulation at more than one sound frequency were asked to estimate the amount of motion on subsequent trials. Of the 46 subjects who participated in Experiment 1 (with frequency varied and other factors held constant), 65% reported visual field shifts with one or more of the six stimulus trains. Subjects reported that "the target appeared to jump a few millimeters laterally and then return to the initial position" (Parker et al., 1978, p. 1915). As expected, significantly more positive responses resulted from the 500- and 1000-Hz frequencies than from the other frequencies tested. Experiment 2, in which the repetition rate was varied, showed the greatest effect at a relatively slow repetition rate (0.9/sec), but Experiment 3, in which onset/offset time was varied, showed an erratic response pattern. No TTS in hearing level was observed. The authors concluded that visual field shifts from acoustical transients are real phenomena, and that people regularly exposed to high-intensity sound may suffer such dysfunctions with or without concomitant loss in hearing sensitivity.

In a subsequent study, Parker et al. (1980) investigated the contribution of other variables to visual field displacements. Among those variables studied were angular acceleration, exposure to an actual rotating visual field, head vibration, target illumination intensity, and alcohol consumption. From the results, the investigators concluded that manipulations that increase subjects' ability to maintain visual fixation will increase the apparent shift in visual field, while disruption of visual fixation (for example, by alcohol) will reduce the visual field shift. They also found that vibration tended to reduce the effect, which they presume to be due to the activation of the acoustic reflex.

4.2.2 Vestibular Effects

Since the early days of jet engine testing and maintenance, anecdotal evidence has appeared linking exposure to intense noise, with such complaints as dizziness, vertigo, nausea, and vomiting, among others (Ades, 1953). Dickson and Chadwick (1951) report that an engineer exposed to jet engine noise said he experienced ". . . a momentary sensation of imbalance accompanied by a lack of power to think . . ." (cited in Harris & von Gierke, 1971). Some of the early BENOX researchers reported equilibrium effects resulting from brief exposures to high noise levels when one ear was occluded with an earplug (Ades, 1953). As a result of siren noise at 140 dB, subjects consistently reported a feeling of being pushed sideways, usually away from the exposed ear, and 1 subject reported difficulty standing on one foot. These effects, however, were not as dramatic from jet engine (broadband) noise at 140 dB. Ades (1953) concludes that the threshold of labyrinthine dysfunction is about 135 to 140 dB and that these effects occur during, but not after, exposure. "We have not the faintest hint of any which could be classed as chronic" (Ades, 1953, p. 69).

Because the end organs for acoustic and vestibular perception are so closely related, it is not surprising that intense acoustic stimulation can result in vestibular effects. Parker et al. (1976) discuss the mechanism by which these effects might occur. They hypothesize that sound of normal intensity produces ac oscillations of endolymph and perilymph, compensated by oscillations of the round window. High-intensity sound produces eddy currents, which are localized rotational fluid displacements (von Bekesy, 1935). High-intensity sound can also produce nonlinear displacement of the stapes, causing a dc volume displacement, the result of which can be a fluid void in the labyrinth. To fill the void, fluid may be displaced along the endolymphatic duct and/or blood capillary pathways, which, in turn, could stimulate vestibular receptors. Figure 24 (from Parker et al., 1976, after von Bekesy, 1935) portrays a model of the labyrinth, indicating release points for fluid displacement resulting from the inward movement of the stapes. The authors conclude that both eddy currents and dc volume displacements serve to stimulate vestibular receptors in humans, when exposed to high levels of noise.

One of the most salient vestibular effects is nystagmus, an involuntary turning or jerking motion of the eyeball, due to vestibular disease or stimulation. Some of the earlier experiments on the vestibular effects of noise used nystagmus as an indicator of vestibular involvement. Parker et al. (1968) found nystagmus in guinea pigs exposed to high levels of infrasound. The fact that eighth nerve section eliminated these responses whereas cochlear destruction did not led the investigators to conclude that acoustical stimulation did indeed activate vestibular receptors. Harris (1972), however, was unable to produce nystagmus in human subjects at high exposure levels. His conditions included 5-sec and 10-sec exposures to a pure tone at 135 dB, broadband engine noise at 140 dB, and a 100-Hz tone at 120 dB, pulsed three times/sec for 2 minutes. Even subjects with a history of motion sickness produced no negative results (Harris, 1972).

Harris and his colleagues performed a series of investigations into the vestibular effects of high levels of infrasound and audible sound. They had been particularly interested in the claims of certain British researchers that infrasound could cause serious performance decrements. According to Harris, Sommer, and Johnson (1976), studies by Evans, Bryan, and Tempest (1971) and Evans and Tempest (1972) found vertical nystagmus resulting from exposure to a 7-Hz stimulus at 130 to 142 dB. In reviewing these studies,

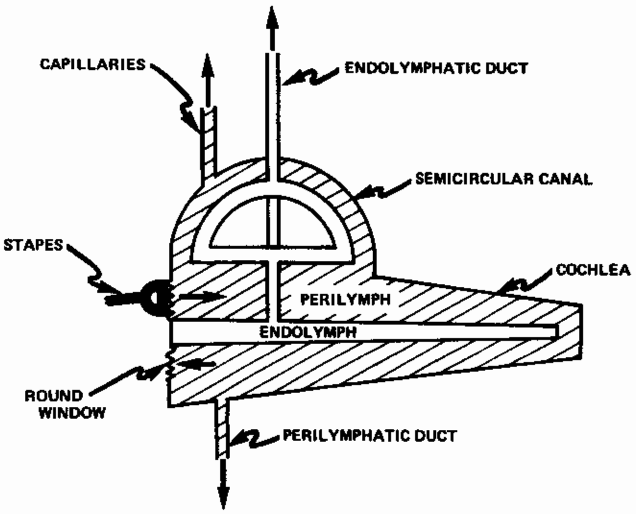

FIGURE 24. Model of the labyrinth, indicating release points for fluid displacement resulting from the inward movement of the stapes. (Parker, Ritz, Tubbs, & Wood, 1976. Reprinted by permission.)

Harris and his colleagues describe them as fraught with methodological and reporting deficiencies, faulty logic, insufficient control for artifacts, and so forth. The authors were unable to elicit nystagmus at levels up to 155 dB (Harris et al., 1976).

Parker and his team were also unable to replicate the effects found by the British researchers using infrasound levels of 112 to 150 dB in guinea pigs, monkeys, and humans (Parker et al., 1976). They suggested, however, that the results of Evans and Tempest might be due to audible components in the sound spectrum, and research with guinea pigs and monkeys confirmed this suspicion. Figure 25, from Parker et al. (1976) summarizes the thresholds found to evoke rotary nystagmus in guinea pigs and monkeys, with data for humans included for comparison. (The human data, from Ades, Graybiel, Morrill, Tolhurst, and Niven, 1957, 1958; and von Bekesy, 1935, include other vestibular effects in addition to nystagmus.)

In a somewhat different approach to the investigation of vestibular effects, Nixon et al. (1966) discovered a task that was sensitive to sound stimulation. This "Rail Task" was then used in a series of experiments. First developed by Graybiel and Fregley (1963), the Rail Task had proved to be a good test for identifying labyrinthine disorders. Nixon, Harris, and their colleagues used 8-foot rails of differing widths and tested subjects' abilities to stand with eyes open, or closed, and to walk. They found that the only condition showing a significant effect from noise exposure was the standing, eyes-open position on the 1.5-inch rail, particularly when one ear received greater acoustic stimulation than the other (Nixon et al., 1966).

An asymmetrical condition, consisting of earplugs in both ears with the addition of an ear muff over one ear, produced an estimated 80-dB sound level in one ear and a 100-dB level in the other beneath the protectors. This condition resulted in a mean change of 8% in the amount of time subjects could balance on the rail, with respect to the control condition. The symmetrical condition, in which the estimated sound level was 80 dB in both ears, produced a slight decrement, but the change was not statistically significant. The authors point out that the estimated exposure levels are quite innocuous from the standpoint of audition (Nixon et al., 1966), but their attenuation estimates may have been somewhat optimistic.

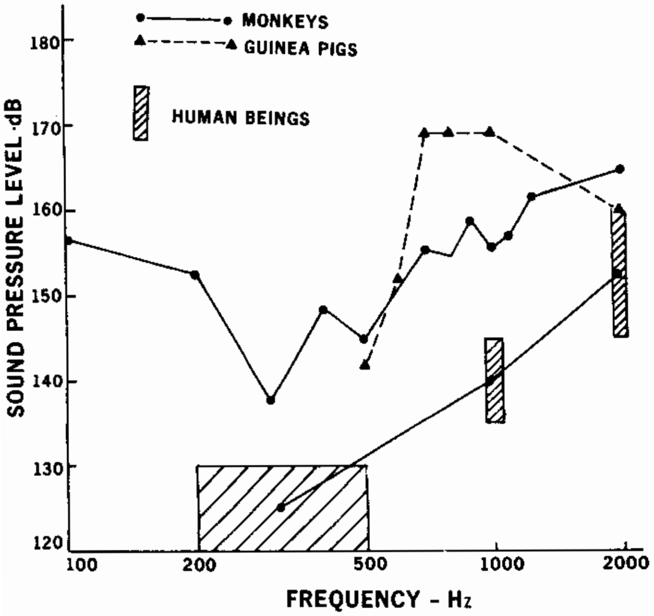

FIGURE 25. Thresholds evoking rotary nystagmus in guinea pigs and monkeys. Human data, including other vestibular effects, are shown for comparison. (Parker, Ritz, Tubbs, & Wood, 1976. Reprinted by permission.)

In the next experiment, Harris and von Gierke (1971) tested the ability of 52 subjects to balance on various rail widths, eyes open and eyes closed, in sound field exposures to broadband noise at levels of 120, 130, and 140 dB. Sound levels under the protectors were assumed to be attenuated approximately 25 dB for plugs alone, and 39 dB for plugs and muffs. The results once again showed greater decrements in the eyes-open than in the eyes-closed condition, which the authors suggest may be indicative of interaction between the vestibular and visual systems. In the eyes-open position, significant differences were found between the 140-dB condition and all other conditions. Surprisingly, the 130-dB and 120-dB symmetrical conditions (plugs in both ears or plugs and muffs occluding both ears) showed systematic improvements over the control condition, although the differences were not statistically significant. In the asymmetrical condition (plugs in both ears plus a muff over one), subjects showed significant performance decrements in two of the three noise conditions. The investigators also measured performance on the rails after termination of noise exposure and found that, consistent with the simultaneous effects, noise exposure tended to improve subsequent performance when the exposure had been symmetrical, but to degrade it when the exposure had been asymmetrical (Harris & von Gierke, 1971).

A follow-up experiment was conducted by Harris and Sommer (1968) to determine the sound frequency most likely to produce decrements on the Rail Task. Also, to eliminate the uncertainty in sound exposure level caused by the use of ear protectors, the investigators presented the stimuli through earphones. Forty-eight subjects listened to pure-tone stimuli of 100, 260, 590, 1500, and 2500 Hz at 95 dB in both ears or 75 dB in one ear and 95 dB in the other, while balancing on rails of various widths. The results showed a small but nonsignificant decrement at 590 Hz, and a significant decrement at 1500 Hz in the eyes-open, asymmetrical condition.

In another study of the effects of sound on equilibrium, Sommer and Harris (1970) used somewhat higher sound levels, again presented through earphones. This time they used broadband, predominantly low-frequency noise to simulate the spectrum imposed by hearing protectors. Overall sound pressure levels were approximately 115 dB to simulate plugs alone, and 100 dB to simulate plugs and muffs. Results on the Rail Task showed significant differences between both the symmetrical and the asymmetrical conditions and the control condition at both noise levels. However, the decrements were not as great as with actual plugs and muffs, worn in higher environmental sound levels (cf. Harris & von Gierke, 1971). Because of this result, the authors conclude that extra-auditory stimulation, presumably through bone conduction, is the cause of the greater effects at higher sound levels. Moreover, they believe that stimulation through bone conduction is not a simple additive factor. If it had been additive, stimulation through earphones should have reduced the decrements proportionally for symmetrical and asymmetrical exposures, which did not occur. Another plausible explanation for the differences in the degree of effect would be that the actual attenuation of the hearing protectors was considerably less than was estimated.

4.2.3 Motor Effects

In an extensive study of the human startle pattern, Landis and Hunt (1939) describe the typical response to a sudden loud sound, such as a .22 caliber revolver: immediate closing of the eyes, followed by a forward motion of the head and neck, hunching of the shoulders, bending of the elbows and knees, contraction of the abdomen, and a forward motion of the trunk. The motion is symmetrical, uninfluenced by postural changes, and rapid, in that it may come and go within ½ sec. Not all features of the response appear in all individuals, but the eye blink invariably occurs. The eye blink's mean latency is about 40 msec and duration about 15 msec. Landis and Hunt found that habituation occurred when the stimulus was repeated at intervals of about 1 to 2 min, that it was very rapid in some individuals, slow in others, and nonexistent in some. The eye blink, however, never habituated, and head movement rarely did. They also found that knowledge of the stimulus can sometimes reduce the level of the response, and increasing the intensity of the stimulus will often increase response magnitude. When the authors studied trained marksmen (New York police officers), they found responses that were only mild or moderate in magnitude, but all subjects exhibited eye blink and head movements, and most showed mild facial distortion (Landis & Hunt, 1939).

In a more recent experiment, May and Rice (1971) studied the startle effects of a .22 caliber pistol fired through a silencer, resulting in a peak sound pressure level of 124 dB. The investigators found performance decrements in a pursuit rotor task for about 2 sec after each shot, after which performance returned to control levels. Repeated exposures improved performance, but scores did not adapt completely over the 16 presentations (a total of 100 minutes).

Harris (1970a, 1970b) also investigated the effects of noise-induced startle on a pursuit rotor tracking task. He notes an observation by Thackray (1965) that some individuals recover cognitive-motor functioning rapidly, while others react sluggishly, even appearing to "freeze." Harris (1970a) exposed 20 subjects to B-duration impulses at a peak sound pressure level of 112 dB, while they were engaged in a pursuit rotor task. He found small decrements for the first few stimuli with respect to control trials, but subjects adapted both within and between sessions. To see if subjects would regain sensitivity after a considerable time interval, Harris (1970b) retested 6 of the original 10 subjects after intervals of 5 to 8 months. The results were not significantly different from the last day of the previous experiment, indicating no return of any noise-induced performance decrements.

Davis and Van Liere (1949) approached the issue of noise-induced startle by studying the effects on muscle tension. They suggested two response modes: the a-response, an initial response, which returns to normal within 1.5 sec, and a b-response, a smaller tension increment with a latency of 1.0 to 1.8 sec, lasting at least 7.5 sec. In response to .32 caliber blanks, subjects' muscle tension did indeed continue for about 7 sec after stimulation, but adaptation occurred in that the b-response duration was shorter in later trials. A-response duration also decreased over repeated trials, but response magnitude did not.

With respect to continuous noise exposure, Stevens (1972) found no systematic relation between noise and degree of muscle tension, although he reports that some subjects did show more tension in broadband noise (115 dB) than in "quiet" (broadband noise at 90 dB).

In a slightly different measure of noise-induced muscular effects, Miles (1953) assessed 4 subjects' ability to squeeze hand dynamometers in a background of jet engine noise at 128 to 135 dB (with subjects wearing earplugs). He found that right-hand performance increased by 2%, left-hand performance decreased by 10%, and total output (both hands) decreased by 2%.

Investigations of the effects of noise on manual dexterity have yielded what appear at first glance to be conflicting results, but these apparent conflicts may well be due to differences in noise exposure level. For example, Miles (1953) gives the results of high levels of jet noise as they affected a two-handed coordination task. Eight subjects, wearing hearing protectors, performed the task while exposed to jet noise of about 130 dB. Scores in noise were 6 to 8% lower than they were in quiet, indicating that subjects needed somewhat more time to perform the same task in noise, even though they showed a tendency to "make haste under the psychological stimulus of intense noise" (Miles, 1953, p. 92).

In somewhat lower noise levels, on the other hand, Weinstein and MacKenzie (1966) found that white noise at 100 dB improved manual dexterity. Subjects were able to turn over a significantly greater number of blocks in the Minnesota Rate of Manipulation Test.

Harris (1968) included a test of manual dexterity along with visual discrimination in the experiment mentioned earlier. He found that the manual dexterity task was somewhat more sensitive to acoustic stimulation than was visual discrimination. Subjects needed significantly more time to manipulate nuts and bolts when they were exposed to the two higher noise levels (130 dB and 140 dB wearing ear protectors), than in levels of 120 dB and below. Surprisingly, there was no significant difference between responses in the symmetrical and asymmetrical conditions, although a difference would have been expected, given the results on the visual discrimination and rail tests. The author suggests that the manual dexterity task was not sufficiently complex to bring out these differences (Harris, 1968).

Sommer and Harris (1970) included the same nuts-and-bolts manual dexterity task in their study of the effects on equilibrium of broadband noise at 100 and 115 dB, presented through earphones. Noise exposure produced small decrements (1% to 3% longer than in the control condition), but none of the differences approached statistical significance. Once again, however, the difference between this experiment and its predecessor might be explained by the likelihood that the actual sound level beneath the hearing protectors was somewhat higher than the investigator had estimated in the previous experiment by Harris (1968).

4.2.4 Summary of Sensory and Motor Effects

Apparently, noise does have some effects on vision, but these effects are too difficult to assess because vital information on the parameters of noise exposure are so often lacking. Some experiments show no effects, whereas others show differential effects, depending on such factors as the light wavelength and the kind of visual effect studied. Noise exposure appears to increase sensitivity for green-blue light and decrease sensitivity for orange-red. Visual discrimination can be decreased by noise, especially with asymmetrical exposure. Studies of CFF suggest decrements for white light, but produce conflicting results for colored light. Perhaps the strongest evidence comes from studies of visual field effects, indicating shifts in visual field perception at noise levels below those originally producing effects in the BENOX experiments. Sound levels of 120 to 125 dB can produce visual field shifts, and it appears that the greatest effect is for tones of 500 to 1000 Hz, with relatively slow repetition rates (0.9 to 1/sec).

Noise also produces reliable effects on vestibular function in certain circumstances. Nystagmus, which is a good indicator of vestibular involvement, has been induced by noise in experimental animals, but the evidence in humans is conflicting. The Rail Task does show reliable effects on vestibular function, but only in certain conditions: eyes-open, 1.5-inch rail, and most often under asymmetrical stimulation (plugs in one ear, plugs and muff in the other). Decrements occur consistently for broadband noise levels of 140 dB (with hearing protection), whereas decrements in the asymmetrical condition can occur at lower levels. Effects are not as great when noise levels of 100 to 115 dB are presented over earphones (simulating the higher levels experienced with ear protectors), but these differences may be due to overestimation of the attenuation achieved by hearing protectors in the higher noise levels.

There is also evidence pointing toward noise-induced motor effects. Impulsive or other sudden, loud sounds can produce a startle response, consisting of a complex of motor responses. Most of these responses habituate, but it appears that the eye blink never does, and some amount of head movement rarely habituates. Some research shows brief but persistent decrements in motor performance after exposure to impulse noise, but other studies provide evidence that motor performance adapts with continued stimulation. Muscle tension, however, appears not to adapt completely. Investigations of the manner in which noise affects manual dexterity yield inconsistent findings, but these inconsistencies are probably due to differences in noise level. It appears that levels up to about 115 dB have little or no effect, with levels of around 100 dB actually improving performance on simple tasks. Levels of 130 and 140 dB, even with subjects wearing hearing protection, do show decrements in manual dexterity tasks.

4.3 NOISE VARIABLES

Despite the tendency not to quantify or report parameters of noise exposure, such as spectrum, duration, and sometimes even level, certain trends have become evident. As one would expect, high-level exposures are more disruptive than low-level exposures, which can sometimes actually facilitate task performance. High-frequency stimuli tend to be more disruptive than low-frequency noise and infrasound. Intermittent and impulsive noise usually have greater adverse effects than continuous noise especially when the noise bursts are aperiodic and/or unfamiliar.

4.3.1 Sound Level

As we have seen from the discussion of sensory and motor effects above, high-level sound stimuli (above about 120 dB) almost invariably produce greater performance decrements than sounds of lower intensity. The BENOX experiments, using high levels of jet engine noise, provide some examples of these effects (Ades, 1953; Miles, 1953), as do the studies at Wright-Patterson Air Force Base that employed the highest noise levels (e.g., Harris & von Gierke, 1971; Mohr, et al., 1965; Parker et al., 1978). These effects occurred, in many instances, even though subjects wore hearing protection. Therefore, they could be expected to be more pronounced in the unprotected condition.

Performance decrements because of high sound levels are not, of course, limited to sensory and motor effects. For example, Miles (1953) found that jet noise of 130–135 dB for durations of about 6 min caused slight decrements in a block assembly test, which involved memory and learning, as well as motor skills.

Broadbent (1957) conducted a study in which various levels of noise, filtered in either a high-pass or low-pass condition, were presented to subjects as they performed a five-choice serial reaction task (cited in Broadbent, 1979). Decrements occurred at the highest sound level (100 dB), and were significant for the high-frequency band. In another experiment, Grimaldi (1958) studied the ability to perform a tracking task and to respond quickly to a visual stimulus. Subjects were tested in various frequency bands of intermittent noise with levels of 70–100 dB. Exposure periods consisted of 10–23 sec of noise, interspersed with 2–13 sec of quiet, totaling 30 min. Significant increases in errors and response times appeared in noise levels at 90 dB and above, and for the higher frequency bands, especially the 2400–4800 Hz band.

On the other hand, quite a few experiments have shown no effects or even improvements in noise levels above 90–100 dB (e.g., Allen, Magdaleno, & Jex, 1975; Stevens, 1972). For example, the series of studies previously cited by Stevens (1972) failed to find significant performance effects for broadband noise at levels as high as 115 dB, with durations as long as 7 hours. Another study by Poulton and Edwards (1974) found improvements in low-frequency noise at C-weighted sound levels of 102 dB (which, however, Broadbent estimates to be an A-weighted level of only 85 dB—see Broadbent, 1979, p. 17–14). The explanation for these differences appears to lie mainly with task difficulty, although many other factors enter in, such as spectral and temporal characteristics and other variables that will be discussed further in subsequent sections. Despite these confounding variables, and as a result of many years of research and study, Broadbent (1971, 1979) has concluded that 95 dB is the level at and above which performance decrements are likely to occur as a result of exposure to continuous noise, and that levels below 95 dB are likely to produce no effect or even beneficial effects. In a more recent summary, Broadbent (1983) points to studies showing that levels as low as 80–90 dB may be disruptive of task performance if the task is sufficiently sensitive (c.f. Jones, 1983, cited in Broadbent, 1983).

4.3.2 Spectrum

Studies described above have indicated that high-frequency noise is more disruptive than low-frequency noise of comparable levels (Broadbent, 1957; Grimaldi, 1958). In fact, as mentioned, low-frequency sound can even have a beneficial effect (Poulton & Edwards, 1974). High levels of infrasound also appear not to be disruptive in that levels of continuous noise as high as 150 dB have failed to produce significant sensory or motor effects (Mohr, et al., 1965). In another experiment, Harris and Johnson (1978) measured the effects of low-frequency noise and infrasound on cognitive performance, consisting of a serial search task and a complex counting task. The four noise conditions included broadband low-frequency noise at 110 dB, a 7-Hz infrasonic tone at several intensity levels from 125 to 142 dB, low-frequency noise combined with infrasound, and an ambient condition. Durations were 7.5 min per trial. The only significant effect that resulted was improvement from a learning effect. The authors conclude that infrasonic levels above 150 dB may be necessary to produce decrements in cognitive performance (Harris & Johnson, 1978).

In a recent study, Landstrom (1988) assessed "wakefulness" based on EEG recordings in response to exposure to infrasound. He found decreased levels of wakefulness from infrasound near perceptual threshold levels at 6 and 16 Hz but not at 12 Hz. In a follow-up field investigation he tested drivers exposed to greater or lesser amounts of infrasound in their trucks. Once again, he found lower wakefulness indices in the drivers exposed to higher levels of infrasound, especially after about 6 hours of driving. Landstrom suggests that moderate levels of infrasound may promote fatigue in working environments, and recommends further investigation of this potential problem.

4.3.3 Temporal Characteristics

4.3.3.1 *Continuous noise.* Continuous noise appears to have little effect on simple tasks, even in relatively high sound levels. Stevens (1972) reports no significant effects on a reaction time task and a fast-speed pursuit rotor task administered during 7-hour durations of broadband noise at 115 dB. Allen et al. (1975) found that performance on a simulated pitch/roll tracking task improved 10% to 15% as a function of noise level, with broadband noise of 75, 95, and 115 dB presented through earphones. In a post-exposure assessment of subjective response, subjects reported that the noise seemed to focus their attention on the task, which, according to the authors, acted to reduce erratic behavior and facilitate performance (Allen et al., 1975).

For more complex tasks, however, such as Broadbent's five-choice serial reaction task (Broadbent, 1957) and a complex tracking task used by Eschenbrenner (1971), performance appears to deteriorate in high noise levels. Broadbent summarizes a number of studies showing that the effect of continuous noise on tasks involving a rapid sequence of actions is to produce greater numbers of errors and occasional slow responses, without decrements in overall response rate. These effects increase markedly in exposure levels above 95 dB, and often occur toward the end of a work period (Broadbent, 1979). Broadbent points out that simple memory tasks are not adversely effected by continuous noise, but some deterioration may occur if the demand on memory is continuous (Broadbent, 1979).

4.3.3.2 *Intermittent noise.* Intermittent noise appears to be more disruptive than continuous noise, especially when the intermittencies are unpredictable. Gulian (1973) states that there is less adaptation with intermittent noise and a greater decline in performance over time. The study cited above by Eschenbrenner (1971) showed a significant effect for temporal pattern, with regularly intermittent noise somewhat more disruptive than continuous noise, and aperiodic intermittent noise significantly more disruptive than either of the other conditions. Broadbent (1979), however, cites studies by Teichner et al. (1963) and Warner and Heimstra (1971) as showing that intermittent noise with a 30% on-time can actually improve performance on a search task, at least for familiar sounds and tasks. Jones (1983) notes that intermittent noise can act as a distractor early in an experiment, but later in the task the same noise can act as an arouser and can improve performance.

Shoenberger and Harris (1965) note that other researchers have found that changes in the noise stimulus may be at least as important as absolute levels. They cite Teichner, Arees, and Reilly (1963) as finding that shifts to lower noise levels produced decrements at least as large as shifts to higher levels on short-term memory and reaction time tasks. The results appeared as a deceleration in the rate of improvement because of learning. In their experiment, Shoenberger and Harris alternated noise levels of 65, 85, 95, and 110 dB for the first 30 min and final 15 min of trials, during which subjects performed a psychomotor task. The results gave moderate support for the findings of Teichner et al. (1963), particularly in the 85-dB to 110-dB condition, but the investigators concluded that the effect would probably be less important in well-learned tasks (Shoenberger & Harris, 1965).

Broadbent (1979) also states that novel or unusual noise can cause a temporary decline in performance efficiency, but that these effects are minimized when individuals adapt both to the noise and to the task. The theory is that a person reacting to an unfamiliar sequence of events is "heavily loaded" and performs additional tasks with difficulty. Practice at the task and familiarity with the noise will reduce the load and enable the individual to perform as before. Only if the sequence of events is truly random would performance continue to be vulnerable. Broadbent believes that "most industrial and military situations involve tasks which are, to some extent, practiced and noises which are to a large extent familiar. Thus the situation of the strange task and the strange noise is of only doubtful practical importance and little experimental interest . . ." (Broadbent, 1979).

4.3.3.3 *Impulse noise.* The discussion of noise-induced startle response in previous paragraphs leads clearly to the conclusion that impulse noise can disrupt task performance, at least for a limited period of time. Once again, simple tasks and self-paced performance may not be affected at all, especially after some amount of adaptation has occurred, but more complex tasks and tasks requiring continuous performance are likely to be more vulnerable. Gulian (1973) reports that the evidence on sonic boom effects is not so consistent, with some studies showing performance decrements, others showing nonsignificant effects, and still others indicating performance improvements.

4.3.4 Summary of Noise Variables

Noise level is, of course, an important variable, with performance decrements generally beginning to occur at levels above about 95 dB. Such decrements are dependent upon numerous other variables, particularly upon the complexity of the task. Simple tasks remain unaffected at noise levels as high as 115 dB or above, even for relatively long durations, whereas it appears that very sensitive tasks can be affected by noise levels as low as 80–90 dB. High-frequency sound is more disruptive than low-frequency sound. Infrasound apparently can be tolerated up to levels of about 150 dB without adverse effects, at least for short durations, but long-duration exposures may produce fatigue effects.

Temporal characteristics make a difference in the effects of noise on performance. Continuous noise has little effect on simple tasks, even at levels exceeding 115 dB (as stated above), and with more complex tasks, generally shows its effects toward the end of the work period. Intermittent noise can be considerably more disruptive, especially if the task or noise is unfamiliar. Aperiodic intermittencies are more likely to produce adverse effects than regular ones, and changes in the noise stimulus may be as important as absolute level. Again the effects are variable, depending on task complexity and other factors. It also appears that adverse effects here are mitigated by familiarity and practice. Impulse noise can be additionally disruptive because it produces a startle response, but these adverse effects can also be expected to habituate, to a large extent.

4.4 NOISE AND OTHER AGENTS

Different stressors affect performance differently. According to Broadbent (1971), heat generally produces performance decrements at temperatures above about 80–85° F (26.7°–29.4° C). Heat stress interacts with an individual's existing state of arousal and may produce performance increments or decrements, depending on an individual's existing state. Sleep loss can also have differential effects, depending upon the type of sleep lost, that is, whether it is REM or non-REM sleep (Broadbent, 1971). Broadbent (1971) states that sleep loss generally affects vigilance and serial reaction tasks by causing an increase in slow reactions or pauses during which there is no reaction. He maintains that the effect of heat stress is to cause a greater number of errors, mainly at the beginning of the session, and noise causes a greater number of errors primarily late in the session. When stressors are experienced in combination, the resulting situation can be quite complex. The effects may be additive, antagonistic, or synergistic, or there may be no effects at all. The outcome will depend on the nature and magnitude of the stressors, the type and degree of difficulty of the task, the individual's state of arousal, and the mechanism through which the stressors act to degrade performance.

4.4.1 Sleep Loss

Broadbent (1979) reports that the five-choice serial reaction test is adversely affected by sleep loss. Although the same task is also degraded by noise (Broadbent, 1957), noise reduces the adverse effects of sleep loss when the two are combined (Wilkinson, 1963). Similarly, Loeb (1980) describes a study by Hartley and Shirley (1977) showing that sleep loss reduces adverse effects caused by noise. It appears that sleep loss lowers the subjects' level of arousal, but noise acts to raise it again.

4.4.2 Gender and Circadian Rhythm

In an investigation of the effects of noise on mental arithmetic, Loeb, Holding, and Baker (1982) found no effect from broadband noise at 95 dB (A). When the data were analyzed according to time of day and gender, however, men showed significant noise-related decrements in the morning, and women did slightly (but not significantly) more poorly in the afternoon. Loeb (1986) cites information from Quinkert and Baker (1984) supporting differences in circadian cycles between men and women. Loeb also refers to research by Baker, Holding, and Loeb (1984), exploring these interactions further, who found that in quiet, women performed better in the morning, and men did better in the afternoon. The introduction of noise reversed this pattern, enhancing men's performance in the morning and degrading it in the afternoon, while enhancing women's performance in the afternoon and degrading it slightly in the morning. The results of these two studies (Loeb et al., 1982; Baker et al., 1984) are not consistent in the direction of effect, although they both show significant interactions between noise, time of day, and gender. The differences may be related to differences between tasks or between measures of performance. The findings of Baker et al. (1984) for male subjects are consistent with those of Sommer and Harris (1972) for noise plus vibration (see following section on vibration).

4.4.3 Incentives

The use of incentives, such as rewards, knowledge of one's performance results, or even punishment, usually acts to improve task performance, presumably by raising the level of arousal. Broadbent (1971) reports that incentive serves to improve performance that has been degraded by heat stress. He also points out that high levels of incentive can actually produce greater errors on a serial reaction task, just as noise does. He believes that noise and incentive reinforce each other, and that they seem to operate under the same mechanism. For example, an experiment by Wilkinson (1963) showed that noise slightly improved performance in a situation in which no incentive was present. When incentive was introduced, in the form of knowledge of performance results, scores improved considerably, but the addition of noise reduced the otherwise strong improvement. Figure 26, from Broadbent (1971) (after Wilkinson, 1963), displays these results. Here, noise alone acts to raise the level of arousal and improve performance. In the motivated state, noise raises the arousal level still further, resulting in overarousal, and consequently degrades performance.

The noise and incentives interaction, however, does not always produce such clear-cut results. In an experiment by Manninen (1985), noise degraded a choice reaction-time task, but incentive served to improve it beyond the scores produced in the control condition. In this experiment the two agents appear to have an opposing effect.

Tafalla et al. (1988) hypothesized that incentive serves to override the negative effects of noise on performance, but does so at a physiological cost. Subjects were exposed to a composite of traffic, office, and unintelligible speech noise at 90 dB(A) in a randomly intermittent pattern, and a control condition of ambient noise at 45 dB(A). During exposure they were engaged in a mental arithmetic task that was scored both on the basis of speed and accuracy. Subjects were instructed to use maximum effort (for which they could also win $50 for the best performance), or "one-half effort." Results showed, as predicted, that noise had no effect on performance during maximum effort. In the low-effort mode noise adversely affected speed but enhanced accuracy. While this enhancement was not expected by Tafalla et al., it is consistent with the enhancement effects noted by other investigators, especially at low levels of arousal (see discussion of Task Variables, Chapter 4). Interestingly, Tafalla and his colleagues found that both systolic and diastolic blood pressure increased significantly in the high-noise, high-effort condition, supporting their notion that noise interacts with incentive to produce unimpaired performance but at a physiological cost.

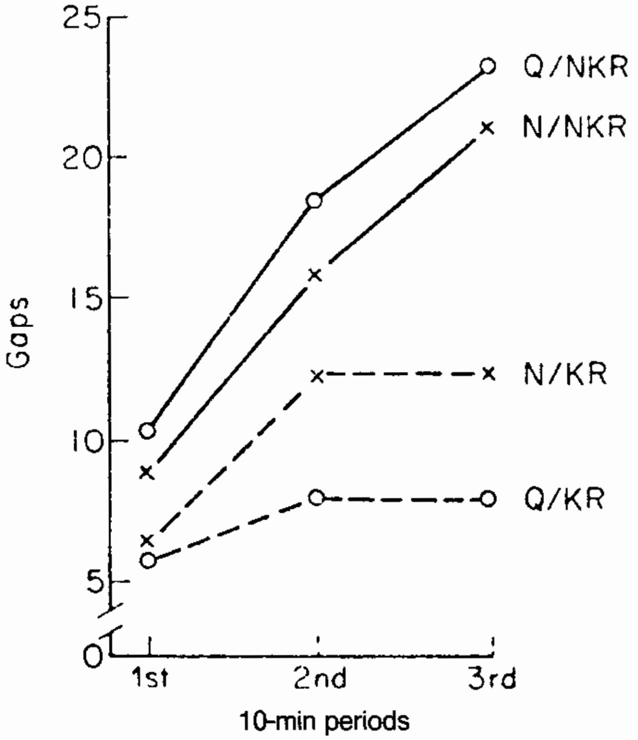

FIGURE 26. Gaps in performance as a function of task duration, noise condition, and incentive. Parameters are noise (N) or quiet (Q), and knowledge of results (KR) or no knowledge of results (NKR). (Broadbent, 1971. Reprinted by permission.)

These kinds of results point out the difficulties inherent in interpreting a multitude of other studies in which the degree to which incentives influence the results may be impossible to judge.

4.4.4 Heat

Hancock and Pierce (1985), in their extensive review of the combined effects of noise and heat on task performance, comment that investigators have found synergistic, additive, antagonistic, and negligible effects. The nature of the effect depends on the type of task, the time of exposure, and the onset order and severity of the stressors. Table 6, from Hancock and Pierce (1985), summarizes most of the research on the combined effects of noise and heat. The authors conclude from this information that the majority of the evidence points toward a relative insensitivity resulting from the combination, and that the two stressors appear to act independently. They point out that many of the studies suffer from methodological errors, in that they lack precise specification of the stressors (a familiar complaint), and they tend to examine only acute effects. Ac-

TABLE 6. Summary of studies on combined heat and noise effects (Hancock & Pierce, 1985).

Study	*Heat level (°C)*	*Noise level (dB)*	*Exposure time (min)*	*Specific tasks*	*Combined effect*
Viteles and Smith	22.8[b] 26.7 30.6	72[c] 80 90	240	Mental multiplication Number checking Lathe test Type coding Discrimeter Location test Pursuit task	No consistent interactions. Suggested interaction only for the lathe test. Potential example of synergy.
Pepler	20.6[a] 37.8	Barely[c] intelligible voice	20	Pursuit tracking task	No interaction or addition effects observed.
Bell, Provins and Hiorns	29.5[a] 63.0	85–95[c] Simulated	Varied by subject	Visual monitoring	Lack of a noise control precludes precise interaction assessment.
Arees	11.9[b] 19.2 31.7	One-minute[c] bursts at 100dB at 30/45 min into task.	60	Visual monitoring	No effect for either heat, noise or combination on mean detection efficiency.
Dean and McGlothen	21.1[a] 26.7 32.2 37.8 43.3	70[c] 110	30	Radar/meter monitoring ten other performance tasks.	No main effects. No interactive effects.
Bell	22[a] 29 35	Random bursts[d] of 1-9s duration at 1-9s intervals 55 95	33	Primary task-pursuit tracking Secondary task-response time	No main or interactional effects for primary task. Suggestion of addivity for secondary task decrement.
Renshaw	22.2[b] 25.6 28.9 32.2	41[d] 80 90 100	90	Five-choice serial reaction task	Indication of synergy for measure of response gaps.
Grether et al.	20[b] 31	80[c] 105	60 35	Tracking Choice reaction time Voice communication Mental arithmetic Visual acuity	Presence of vibration prevented discrete effects of heat and noise being distinguished.
Grether et al.	21[b] 31	80[c] 105	60 35	As above with a telephone test substituted for voice communication	Combined heat and noise effects not distinguished separately.
Bowman and von Beckh	24[a] 51	66[d] 85	60	Tracking Response time	Presence of acceleration buffett and low light obscured heat and noise effects.
Loeb and Jeantheau	52[a]	125[c]	225	Visual monitoring	Heat, noise and vibration in combination, no distinguishable effect of heat and noise alone.
Poulton and Edwards	19.0[b] 34.4	80[e] 102	90	Tracking Visual monitoring	Some statistical indications of both synergy and antagonism. Possible artifact of methodological approach.
Wyon et al.	22[a] 30	50[d] 85	30	Serial choise response Visual vigilance task	Some indications of synergy and antagonism in selected groups but small number of subjects per cell in study.

Notes. [a] Dry bulb temperature [b] Effective temperature [c] Noise scale not reported [d] dB (A) [e] dB (C).

cording to Hancock and Pierce, decrements are more likely when deep body temperature is affected, which would occur only during relatively long exposures. This is in contrast to Broadbent's opinion that decrements from heat stress occur early in the session (Broadbent, 1971). The authors believe that a "conservative course of action would be to regard these stressors as slightly synergistic in combined effect and to act accordingly" (Hancock & Pierce, 1985).

In one experiment not cited by Hancock and Pierce, Manninen (1985) tested the effects of noise, vibration, heat, and incentive, both singly and in various combinations. Reaction time on a choice reaction task showed decrements for both heat and noise alone and somewhat greater decrements for the combination, but the effect was not completely additive. Interestingly, heat had a significantly beneficial effect when it was added to vibration.

4.4.5 Vibration

In a series of experiments, Harris and his colleagues investigated the combined effects of noise and vibration on task performance. Harris and Shoenberger (1970) found, not unexpectedly, that vibration alone (0.25 g at 5 Hz) produced decrements in both the horizontal and vertical dimensions of a tracking task, and also in a reaction time task. Noise alone (broadband at 110 dB) caused decrements on only the vertical dimension of the tracking task, and a small, statistically insignificant effect on the reaction time task. The effect of noise plus vibration on the tracking task was additive, with no effect for the combination on the reaction time task. To avoid the mechanical effects of vibration, Harris and Sommer (1971) tested essentially the same conditions on a mental arithmetic task. Neither noise nor vibration produced adverse effects alone, nor did vibration plus noise at 80 or 90 dB. However, vibration combined with noise at 110 dB produced significant decrements.

Grether et al. (1971) used broadband noise at 105 dB and vibration of 0.3 g at 5 Hz, along with heat at 120° F to test subjects' responses on the two-dimensional tracking task and the mental arithmetic tasks, as well as a choice reaction task. Noise alone showed no significant effects except on the reaction time task. Combined stressors showed no significant effects over any of the individual stressors. In fact, the tracking task was less affected by the combinations than by the single stressors.

Because of the evidence that circadian rhythm affects task performance, Sommer and Harris (1972) tested the effects of the original vibration and noise combination (0.25 g at 5 Hz and 110 dB) on mental arithmetic at 6 a.m. and 3 p.m. They found the expected improvements at 3 p.m. (over 6 a.m.) in the no-stress condition, and a slight decrement for the noise plus vibration condition, relative to the no-stress condition at 3 p.m. The interaction between time of day and stress (noise plus vibration) led these authors (like Loeb and his colleagues) to conclude that circadian rhythm may affect these kinds of experiments.

In an attempt to investigate the effects of slightly lower levels of noise and vibration, Sommer and Harris (1973) used the same two-dimensional tracking task, with vibration of 0.10 g at 6 Hz, and broadband noise at 100 dB in somewhat longer sessions. Noise alone produced no significant effects, whereas vibration produced adverse effects in both dimensions. In combination, noise actually reduced the adverse effects of vibration. When Harris and Sommer (1973) raised the noise level back to 110 dB, the combined effect was additive once again.

Finally, Harris and Shoenberger (1980) changed the parameters to noise at 100 dB(A), vibration to 0.36 RMS g (complex rather than sinusoidal vibration, which is more typical of actual operations), and an experimenter-paced cognitive task (the Complex Counting Task). The results showed significant decrements each by noise and vibration alone. The combination produced performance that was slightly poorer than the control condition, but the differences did not reach statistical significance. Surprisingly, the combined stressors produced less effect than either stressor alone. An experiment by Manninen (1986) also found no significant effect from noise plus complex vibration, but did show some increase in effect (body sway) from noise in combination with sinusoidal vibration.

4.4.6 Psychological Factors

Certain psychological variables interact with noise exposure to affect job performance. Like incentives, they are usually uncontrolled, and their effects will not be readily apparent.

Some investigators have categorized their subjects as introverts and extroverts to investigate personality variables in combination with noise. Broadbent (1971) mentions research in which noise improved performance of extroverts early in the morning but not later in the day, while introverts showed no effects. He also cites an experiment by Davies and Hockey (1966), showing that noise improves vigilance performance of subjects classified as extroverts under certain conditions. These experiments support the theory that extroverts operate at chronically lower arousal levels than introverts, and noise raises their arousal levels (especially in the morning), enhancing task performance. Broadbent's (1971) own research, however, indicated that the correlation between noise effects and introversion/extroversion was unstable, and was complicated by another personality dimension, neuroticism.

Another confounding variable, whose effects are often unknown or overlooked, is the psychological "set" created by the instructions given to the subjects. Mech (1953) investigated this problem by presenting four groups of subjects with four slightly different sets of instructions. Group A, the control group, was told that the experiment concerned the effects of noise on work. Group B was told the same, along with the suggestion that previous subjects had performed better in noise. To Group C it was suggested that previous subjects had done better in quiet, and to Group D it was suggested that previous subjects had performed more poorly in noise at first, after which they had adapted and performed better in noise. Subjects performed mental arithmetic while listening to "verbal" noise (competing message) at a level of 70 dB, over an 8-day period. The results, displayed in Figure 27, showed a statistically significant difference in performance among the four groups, with each group performing according to its pre-experimental set.

A more recent experiment by Gawron (1982) failed to replicate Mech's results. Subjects who were told that noise facilitated performance did indeed have their best performance on a digit-canceling task in the highest noise levels, but subjects who were told that noise hinders performance showed no significant decrements. Also, there was no significant facilitation in this group for the two other tasks evaluated. The author mentions that psychological set did interact with task complexity as well as noise level, but gives no details about this interaction. Probably the most salient reason for the differences between these two experiments lies in the duration: Gawron's experiment consisted of a series of six 4-min trials, presumably over a single day, while Mech's subjects worked a total of 4 hours, spread over an 8-day period. Only after the first day did the differences in Mech's groups become apparent.

In these experiments the suggestions were quite overt, and the influence was intentional. In most investigations of noise and performance, one would assume that the instructions are standardized and carefully constructed so as to avoid this kind of bias. However, to the extent that the experimenter's prejudice might be intuited by eager subjects (who are usually students or young military volunteers),

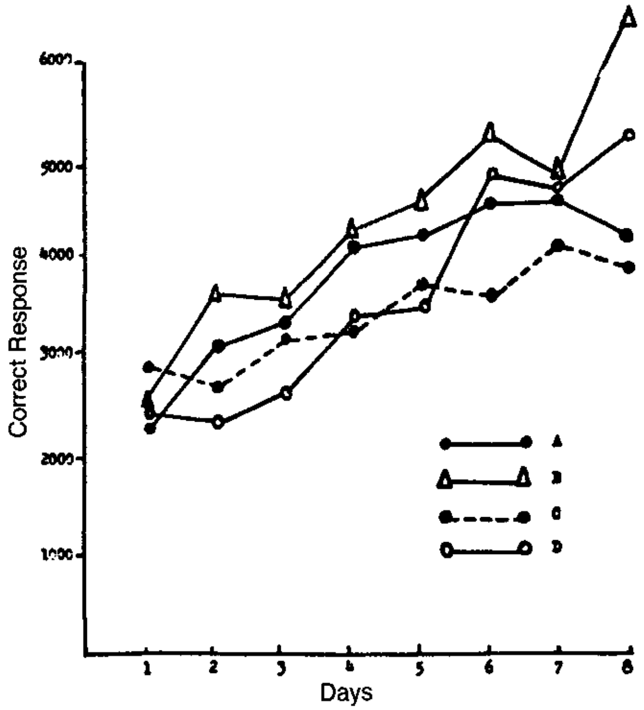

FIGURE 27. Performance on a mental arithmetic task while listening to "verbal" noise, as a function of days over which the task was presented. Parameter is pre-experimental "set."
Group A: Control
Group B: Instructed that previous subjects performed better in noise
Group C: Instructed that previous subjects performed worse in noise
Group D: Instructed that previous subjects had performed worse in noise at first, then adapted and performed better
(Adapted from Mech, 1953. Reprinted by permission.)

the experimental results will be influenced to an unknown degree.

4.4.7 Summary of Combined Stressors

One thing is quite clear from the above discussion, and that is that the combined effects of noise and other stressors are extremely complex. The direction and degree of effect depend on many factors: an individual's state of arousal, including gender; circadian rhythm; the nature of the task; the magnitude and duration of the stressors; and personality and other psychological factors. They also depend on whether the stressors operate under similar or antagonistic mechanisms, although it is not always clear what the various mechanisms are.

Noise and sleep deprivation appear to act in opposite directions, although it is conceivable that certain conditions of sleep deprivation (e.g., loss of REM sleep) can result in overarousal. Both noise and incentive appear to act as arousers. Incentive usually improves performance, but the addition of noise reduces these gains. Because incentive (or the lack thereof) is present to some extent in virtually every experiment, it is very difficult to know the extent to which it influences the effects of noise alone. The evidence on noise combined with heat is mixed: some synergisms, some antagonisms, and sometimes no effects. Most of the exposures are acute, however, so longer exposures deserve some caution. The series of experiments by Harris and his colleagues, which studied the combination of noise and vibration, showed no effects or even subtractive effects in moderately high levels, up to 105 dB. Above that level the effects appear to be additive, at least when noise is combined with sinusoidal vibration, which produces greater decrements (in combination with noise) than complex vibration.

Personality factors may also combine with noise exposure to affect noise in complex ways. These factors appear to interact with level of arousal, or at least with changes in level of arousal. Psychological "set" may influence an individual's expectations of noise effects, thereby either enhancing or degrading performance.

4.5 TASK VARIABLES

4.5.1 Simple Tasks

As we have pointed out above, simple tasks are not adversely affected by noise, even at relatively high sound levels. Broadbent (1971) suggests that the reason why many of the early experiments on noise and performance showed no effects was because they used tasks in which information was handled at fairly low rates; crucial information was predictable and interspersed with periods of no information. In other words, these tasks were not sensitive to momentary disruptions of information intake, as vigilance or serial reaction tasks would be (Broadbent, 1971). Simple clerical and intellectual operations rarely show impairments from noise at sound levels between 80 and 100 dB, and sometimes as high as 140 dB (Broadbent, 1979). Reaction time remains unimpaired so long as the signal is predictable (Broadbent, 1979), and as we have demonstrated, most sensory and motor performance is unaffected up to fairly high levels of noise.

4.5.2 Tasks Requiring Continuous Performance

On the other hand, tasks involving continuous performance appear to be more vulnerable. Broadbent (1979) observes that noise produces a focusing of behavior, with greater concentration on the task. When attention is diverted, especially by intermittent (or impulsive) noise, momentary inefficiencies will occur. The end result is increased variability in performance, even though average performance may not change. In other words, noise will produce momentary lapses, for which subjects will compensate later in the task by improved or more rapid performance. Broadbent (1979) gives several examples of such cases: In a clerical task involving the cancellation of digits, intermittent noise up to about 90 dB caused variations in performance at different times in the test, with no overall performance decrement (Sanders, 1961). In a serial reaction experiment, subjects showed no difference in average performance, but reaction times were considerably slower after bursts of intermittent noise (Fisher, 1972). Another continuous task involving decisions about a series of visual stimuli was disrupted by bursts of noise at 95 dB (but not at 85 dB), causing performance decrements for 20 to 30 sec after the noise burst (Woodhead, 1959, 1964).

Broadbent (1979) points out that some tasks of continuous performance may be more vulnerable than others. For instance, a tracking task such as driving on a straight road will be relatively insensitive to intermittent disruptions. Rapid driving on a difficult course, however, where every lapse could have serious consequences, would be a different matter. In some tracking experiments, subjects have actually shown improved performance during noise exposure. A good example is the tracking experiment mentioned previously by Allen et al. (1975), in which subjects reported that noise had enabled them to focus their attention on the task. Other, more complex, tracking tasks, however, have shown decrements (e.g., Eschenbrenner, 1971).

Harris and Filson (1971) tested subjects with a cognitive test of continuous performance, a serial search task. They noted that Broadbent had emphasized certain conditions as necessary to produce adverse effects: The test durations should be a minimum of 30 to 60 min; the task should be experimenter-paced, requiring the subjects' continual attention; and the noise level should be 100 dB or above. To test these parameters, Harris and Filson exposed subjects to broadband noise at 105 dB for 36-min durations daily over a period of 5 days. One group's exposure was interrupted with three rest periods, whereas the other group's exposure was continuous. The results showed significant performance decrements for the no-rest group, especially toward the end of the experimental period, indicating that the subjects did not adapt to the noise stress. These findings show that continuous performance can be disrupted by noise, if certain conditions are present.

4.5.3 Intellectual Function

As mentioned earlier, simple intellectual and clerical tasks are not usually degraded by noise, even up to very high noise levels. In his review of the effects of noise on intellectual function, Loeb (1980) cites some studies showing differential effects of noise on memory and mental arithmetic. It appears that sound levels of 80–90 dB can actually improve primary memory, for example, of stimulus content or order of items, while impairing incidental memory, such as stimulus location (Davies & Jones, 1975; Hockey & Hamilton, 1970). Noise at 85 dB was found to improve visual memory of recent items, but degraded memory for less recent ones (Hamilton, Hockey, & Rejman, 1977). Loeb also cites studies showing that noise can impair auditory memory (Murdock, 1967; Rabbitt, 1966), but one has to consider the possible effects of masking, especially spread-of-masking effects at high sound levels. One experiment avoided potential stimulus masking by presenting the stimuli visually and attempting to restrict subjects' internal auditory or proprioceptive feedback by presenting white noise at 100 dB through earphones and by clamping the subject's tongue or requiring him to hold his breath. Such feedback restrictions appeared to impair short-term memory, and the combined effects of internal auditory and proprioceptive restrictions were additive (Adams et al., 1969, cited in Loeb, 1980). Although there are obvious discomforts (and possibly distractions) inherent in holding one's breath and having one's tongue clamped, there is additional evidence that noise may adversely affect the internal speech necessary for short-term memory (Wilding & Mohindra, 1983).

With respect to mental arithmetic, Loeb (1980) reports that short-term memory can be affected, but the results are complex. For example, in one experiment (Park & Payne, 1963), noise produced no overall decrement, but increased performance variability (as in tasks requiring continuous performance, described above). In another, noise degraded performance only during the presentation of a number to be memorized, but actually improved performance when it was presented during the calculation period (Woodhead, 1964).

There is evidence that noise is disruptive to complex intellectual functioning. For example, Harris and Shoenberger (1980) showed that noise at 100 dB(A) could disrupt a short-term memory task that was sufficiently difficult. This experimenter-paced task required subjects to keep simultaneous count of the number of flashes of lights located in three positions.

4.5.4 Vigilance

There is good agreement that noise can adversely affect vigilance, which requires in individuals "a readiness to respond to infrequent, low-intensity signals occurring at unpredictable temporal intervals" (Buckner & McGrath, 1963, p. vii). McGrath (1963) points out that many vital military missions require vigilant observers, and that our national security is dependent upon the efficiency of missile detection and early-warning systems.

Broadbent (1971) states that the chances of detecting a stimulus during a vigilance task depend on the probability of the stimulus, an individual subject's state of arousal, and any change in responsiveness when the watch continues for a long period of time. If for some reason an individual's internal criteria for reporting a signal should change, the outcome in terms of performance efficiency can also change (Broadbent, 1971). Noise can effect such changes.

Hockey (1970a) summarized the evidence to date on the effects of noise on vigilance. These findings are reprinted in Table 7. In general, Hockey concluded that the most important variable was task complexity: that multi-source tasks or tasks with high signal rates resulted in decrements, and that single-source tasks or tasks with low signal rates showed improvements or no effects from noise exposure. Hockey's experiments (1970a, b) demonstrated the complexity of the manner in which noise affects vigilance performance. The primary task was a pursuit-tracking task in the center of the visual field, and subjects were instructed

TABLE 7. Effects of noise in vigilance tasks: The importance of signal rate and number of sources on the direction of the effect (from Hockey, 1970a).

Author(s)	No. of sources	Signal rate (per hour)	Noise conditions	Effect on performance
(1) Broadbent (1951)	20	10	100 vs. 70 dB	decrement
(2) Broadbent (1954)	20	10	100 vs. 70 dB	decrement
(3) Broadbent and Gregory (1963)	3	72	100 vs. 75 dB	decrement
(4) Jerison (1959)	3	82	112 vs. 79 dB	decrement
(5) Broadbent and Gregory (1965)	3	200	100 vs. 75 dB	decrement
(6) McGrath (1963)	1	72[a]	72 dB (varied vs. steady)	decrement decrement
(7) Broadbent and Gregory (1965)	1	200	100 vs. 75 dB	decrement
(8) Kirk and Hecht (1963)	1	30	65 dB (varied vs. steady)	increment
(9) Jerison (1957)	1	30	114 vs. 83 dB	none
(10) McGrath (1960)	1	24[a]	72 dB (varied vs. steady)	increment
(11) Broadbent and Gregory (1965)	1	70	100 vs. 75 dB	none
(12) Davies and Hockey (1966)	1	24	95 vs. 65 dB	increment
(13) Davies and Hockey (1966)	1	48	95 vs. 65 dB	none
(14) Tarriere and Wisner (1962)	1	16	90 vs. 35 dB	increment

Note. All tasks using more than one source (nos. 1 to 5) are impaired by noise. In the two single-source tasks that show impairment (6 and 7) the signal rate was manipulated within the experiment. A higher rate gives impaired performance and the lower rate either no effect (11) or improvement (10). This trend is also evident in 12 and 13, where increasing the signal rate cancels out the facilitatory effect of noise.

[a] Event rate was varied in these experiments, from one stimulus every 0.66 sec to one every 2 sec.

From Hocky, G. R. J. (1970a). Reprinted by permission.

of this fact. The secondary task consisted of monitoring six lights spaced around the window housing the tracking exercise. Broadband noise at 70 dB ("quiet") and at 100 dB was presented in two 10-min segments for each condition, and again after a 1-week interval. Subjects' performance on the primary (tracking) task improved slightly over time in the noise condition, although it did not improve in the quiet condition. Performance on the secondary (vigilance) task improved for the centrally located lights, but was significantly degraded for those coming from the peripheral sources. The author concluded that noise produces a shift in the distribution of efficiency over various components of the task (Hockey, 1970a). In a subsequent experiment, Hockey found that the difference in ability to detect central and peripheral signals was not so much a question of location as it was the subjects' perception of the probability of stimulus occurrence (Hockey, 1970b).

Broadbent (1979) discusses many of the important parameters concerning noise and vigilance. He points out that moderate levels of noise and music can improve the performance of vigilance tasks, citing McGrath (1963) and Davies, Lang, and Shackleton (1973). Subjects categorized as introverts show no improvement in noise levels of 95 dB, whereas those categorized as extroverts do (Davies & Hockey, 1966). Noise tends to reduce the number of responses when subjects are unsure (Broadbent & Gregory, 1963, 1965), and increases the number of "confident" detections (Hockey, 1973). Broadbent (1979) also points out that the effects of noise depend on task complexity. For example, there was no effect on vigilance in white noise at 100 dB when the dials to be observed were easy to see. When they were more difficult to see, however, noise at 100 dB caused decrements (Broadbent, 1954). Broadbent summarizes by stating that noise will adversely affect vigilance if (a) the level is above 95 dB, (b) the length of the watch is long, (c) the signal may come from a number of sources, (d) the situation does not encourage caution, and (e) the signal is difficult to see (Broadbent, 1979).

4.5.5 Complex Tasks

By now it should be evident that complex tasks are considerably more vulnerable to noise exposure than simple ones. Gulian (1973) points out several ways in which tasks can be made more complex. Investigators can multiply the sources of stimuli, such as dials or lights to be monitored; increase the intrinsic difficulty of the task; make the temporal requirements more stringent; or give the subject simultaneous tasks.

An example of an intrinsically difficult task is the tracking task used by Eschenbrenner (1971). Subjects viewed simulated earth movements as if they were orbiting over the earth's surface, and used a hand control to compensate for perceived motion. White noise at 50, 70, and 90 dB was administered during each 40-sec trial for 20 trials in each session. Temporal patterns were continuous, and intermittent with a 2-sec on time, in which they were presented in both periodic and aperiodic patterns. Somewhat surprisingly, all noise patterns produced significant performance decrements, although the aperiodic pattern produced significantly poorer performance than the continuous or periodically intermittent noise. The author concludes that "Manual image motion compensation is a complex psychomotor task that requires continuous processing of sensory information and is, therefore, extremely susceptible to the distracting effects of noise" (Eschenbrenner, 1971, p. 62).

Most of the complex tasks used to assess the effects of noise have been dual or combined tasks. For example, Broadbent (1979) describes experiments involving intentional and incidental memory. When subjects are instructed to remember words, their performance improves in noise, but when asked unexpectedly to recall the location of the words, their performance deteriorates (Davies & Jones, 1975; Hockey & Hamilton, 1970).

As explained above, experiments by Hockey (1970a, b) used as a primary task a pursuit-tracking task, and a vigilance secondary task, with the result that performance on the secondary task was degraded by noise when subjects perceived signals in the periphery as being less probable. In another experiment involving dual tasks, Finkleman and Glass (1970) presented subjects with broadband noise at 80 dB(A) in predictable and unpredictable intermittency patterns. They found performance on a primary tracking task to be unaffected for either noise pattern, and that significant decrements for a secondary digit recall task occurred only in the unpredictable condition. Glass and Singer (1972) interpret these results as showing that noise must be especially aversive to degrade task performance.

Loeb and Jones (1948) extended Hockey's (1970a, b) studies by performing two experiments with tracking as the primary task and vigilance as the secondary task, and two with vigilance primary and tracking secondary. Each task had either a "bias," with the probability of the vigilance stimulus toward the location of the high-priority task, or "no bias," meaning equal probability of the stimuli. The investigators state that there were no "appreciable" effects of noise on the vigilance task, regardless of task priority, but they present no data to support this finding. The authors state that their results were not in agreement with those of Hockey. However, noise did significantly degrade the tracking task in both the bias and no-bias conditions. According to Loeb (1980), this task was more difficult than the tracking task employed by Hockey, which may help explain the differences on tracking performance.

Loeb (1980) reports other experiments that were stimulated by Hockey's original studies (1970a, b). One by Forster and Grierson (1978), which found no effects, used conditions similar to Hockey's, except that the noise level was 91 dB instead of 100 dB, and the tracking task was more difficult. Another by Finkleman, Zeitlin, Fillippin, and Friend (1977) showed decrements on both a primary tracking task and a secondary digit recall task, resulting from noise at 93 dB(A).

4.5.6 Summary of Task Variables

Noise exposure usually has no adverse effects on simple routine tasks in which information is handled at low rates, crucial information is predictable, and constant attention is not required. In fact, noise can even improve the performance of monotonous tasks, presumably by elevating one's level of arousal. Tasks requiring continuous performance, such as tracking tasks, may be momentarily disrupted by noise, but subjects usually can compensate by improved or more rapid performance, leaving average performance unchanged. If the task is sufficiently demanding, these momentary lapses can adversely affect overall performance, especially if noise levels exceed 100 dB and performance continues for more than 30 min.

Intellectual function, such as short-term memory and mathematical calculation, can also be momentarily disrupted without decrements in overall performance. When these tasks become more complex, noise is more likely to affect them. For example, incidental memory is likely to be impaired whereas primary memory is unaffected. The mechanism may involve the interference by noise with internal auditory and proprioceptive feedback.

Vigilance performance appears to be more easily disrupted by noise exposure. Although moderate levels of noise once again may improve performance, especially if the signal originates from a single source, higher exposure levels are likely to degrade performance. Performance is more readily degraded by noise when the signal emanates from numerous sources, cautious behavior is not encouraged (i.e., signal probability is high), and the duration of the watch or experiment is long.

Task complexity has been identified in numerous instances as being a crucial determinant of the effects of noise on performance. Decrements occur either because the task is inherently demanding or because an individual must perform two or more tasks simultaneously. Performance on the primary task usually remains unaffected, or even improves, whereas performance on the subsidiary task deteriorates. As above, the nature and degree of effect depend on noise level, the inherent difficulty of the task, and the subject's perception of signal probability. Also, the temporal pattern of the noise appears to be important, with unpredictable noise bursts being more disruptive than predictable ones.

4.6 AFTER EFFECTS

Although most researchers have looked at noise and its concomitant effects on task performance, a few have examined the after effects, with some interesting results. Probably the classic study in this area was conducted by Glass and Singer (1972). The noise stimulus was a sound-on-sound recording of two people speaking Spanish and another speaking Armenian, mixed with the sounds of various office machines. The result was broadband noise of approximately 150–7000 Hz, with the mode at 700 Hz. Presentation levels were "loud" at 108 dB(A) and "soft" at 56 dB, presented in a fixed intermittent pattern of 9-sec bursts, once per min for 23–25 min, and in a pattern in which burst and interval durations varied randomly (while maintaining equivalent sound energy). Exposure conditions were, therefore, loud periodic, loud aperiodic, soft periodic, soft aperiodic, and no noise. Subjects performed simple cognitive tasks during the noise exposure periods, and afterward were given four puzzles, two of which were insoluble (a measure of tolerance for frustration), and subsequently a proofreading task. The authors considered these tasks relatively simple.

Resulting performance on the insoluble puzzles showed significant decrements for the average number of trials for the 108 dB(A) versus the 56 dB(A) noise conditions. Subjects also showed poorer performance after the aperiodic noise than after the periodic noise, and, in fact, the deficits following the soft aperiodic condition were greater than those following the loud periodic condition. The proofreading task showed no differences in the number of lines read for either the periodic or aperiodic noise conditions, but there were significantly more errors following the aperiodic noise condition. Errors also increased following the loud noise conditions as opposed to the soft noise conditions, but the difference did not reach statistical significance.

Glass and Singer (1972) performed another experiment to explore the predictability concept further. This time they preceded the 108 dB(A) aperiodic noise burst with a signal light in one condition, presented noise and an uncorrelated light in another, and noise without light in a third condition. The results showed that predictability made a significant difference in frustration tolerance, but not in proofreading accuracy. Although the authors were unable to explain the lack of effect on the proofreading task, they concluded that in general, the principal effect of noise on task performance is caused by the absence of predictability, and that this effect is greater after than during the noise exposure, in the absence of "task overload." They hypothesize that people may manage to control their "affective reactions" until the noise ceases, at which time it is no longer necessary to maintain maximum performance. They also conclude that perceived control over the noise is the crucial factor, determining the difference in effect between predictable and unpredictable noise bursts.

Loeb (1980) reports that the research by Glass and Singer (1972) has stimulated other similar investigations. For example, Percival and Loeb (1980) replicated the Glass and Singer experiment with the same tasks and general design, using a tape of the earlier investigators' complex noise stimulus with the same intermittency schedules. This time the peak A-weighted sound levels were 95 dB in the fixed- and random-schedule noise conditions, with a continuous level of 46 dB(A) in the control condition. Percival and Loeb found no significant effects during the simple tasks performed during exposure. Once again, subjects made significantly fewer attempts to solve insoluble puzzles after noise exposure, and the effect was greater after the unpredictable than after the predictable noise bursts. No effect was evident for the proofreading task. According to Loeb (1980), other researchers also have been unable to replicate the proofreading effect (Moran & Loeb, 1977; Wohlwill, Nasar, DeJoy, & Foruzani, 1976), but studies by Wohlwill et al. (1976) and Rotton, Olszewski, & Charleton, and Soler (1978) did replicate the effect on insoluble puzzles. Loeb notes that when the noise stimulus was meaningful speech, the effect was greater than when it consisted of noise without speech. Consequently, he suggests that the meaning of the noise (speech sounds vs. nonspeech sounds) may be responsible for the difference (Loeb, 1980).

In an attempt to probe the particular characteristics of noise that produce behavioral after effects, Percival and Loeb (1980) repeated their experiment using four types of intermittent noise: (a) normal aircraft flyovers, (b) combinations of aircraft flyovers that had been acoustically modified to produce sudden onsets and offsets as well as randomly fluctuating peaks, (c) white nose with sudden and unpredictable onset and offset, and (d) original Glass and Singer noise. The investigators found that the Glass and Singer noise and the modified aircraft noise produced significantly lower levels of tolerance for frustration on the puzzles than the other types of noises. They note that the only physical characteristics these two noises have in common are multiple and unpredictable changes in sound level within randomly scheduled intervals. They also suggest that cognitive aspects may play a role in that both of these noise stimuli were unusual combinations of real-world sounds. Another possible explanation could be differences among stimuli in total sound energy, because the authors do not mention controlling for this aspect.

The results of these investigations show that high levels of noise can produce adverse effects on performance after the exposure is discontinued, mainly on tasks that are sensitive to frustration intolerance. The effects are greatest when the noise stimuli contain speech sounds and when they are characterized by unpredictable changes in sound level.

4.7 EFFECTS ON SOCIAL BEHAVIOR

There is an extensive literature concerning the effects of noise on social behavior, and a complete review of this topic is beyond the scope of this report. However, it would be useful to summarize some of the findings at this time.

The following studies are discussed in greater detail by Cohen and Weinstein (1981) in their review of the nonauditory effects of noise: Mathews and Cannon (1975) found in a laboratory experiment that fewer subjects were willing to help someone who had "accidentally" dropped materials when background noise levels were 85 dB than when they were 65 dB. In a subsequent field study, the same results were demonstrated in a background of lawn mower noise. This time the addition of a cast on the "victim's" arm enhanced helping behavior under quiet conditions, but failed to do so during noise exposure. In another such experiment, Sauser, Arauz, and Chambers (1978) found that subjects recommended lower salaries for fictitious employees when exposed to office noise at 70–80 dB(A) than in quiet.

Sherrod and Downs (1974) exposed subjects to three noise conditions: soothing (seashore), distracting (containing speech), and distracting with perceived control. After the noise exposure had terminated, helpful behavior was assessed, with the result that subjects were most helpful after the soothing noise, and least helpful after the distracting noise with no perceived control. In another study of noise after effects, Donnerstein and Wilson (1966) found that subjects without perceived control over their noise exposures gave more shock to their fellow subjects than those with perceived control. Finally, Siegel and Steel (1979) found that subjects were less able to discriminate between behaviors and make attributions of responsibility when they were exposed to broadband intermittent noise at 92 dB than in quiet. (Above studies cited in Cohen & Weinstein, 1981.)

Jones (1983) cites studies by Boles and Hayward (1978) and Korte, Ypma, and Toppen (1975) showing that increases in noise level reduce the number of subjects willing to grant interviews on the street. He also cites Korte and Grant (1980) as finding that aversion to noise may speed a subject's passage through a noisy setting. He points out that some of these experiments may have been influenced by the presence of a verbal response requirement, and mentions that Korte et al. (1975) did not find an increased number of people ignoring the request for an interview (Jones, 1983).

Broadbent (1979, 1983) notes the increased risk of hostile behavior associated with noise exposure and cites additional evidence suggesting that subjects will give each other increased amounts of shock and noise when they themselves are exposed to noise (Broadbent, 1979). He also cites evidence that noise increases anxiety levels (Broadbent, 1983), which may, at least in part, account for the increases in antisocial behavior.

4.8 THEORY

The preceding discussion on sensory and motor effects has provided considerable evidence that quite high levels of noise exposure can produce adverse effects on performance by acting directly on vestibular receptors and other sensory processes (as shown in experiments by Mohr et al., 1965; Parker et al., 1968, 1976, 1978; and Reschke et al., 1975; etc.). The probable mechanisms have been outlined earlier. But what is the mechanism for effects from more moderate levels of noise exposure?

There is widespread agreement that noise causes increases in an organism's level of arousal through stimulating or "toning up" the reticular formation. The resulting increase in arousal level has provided one of the original explanations for the effects of noise on performance, both positive and negative. As mentioned above, a certain amount of stress (by noise or similar stressors) can enhance task performance, especially when the task is routine and monotonous. If, however, an individual is already optimally aroused for a certain job, the addition of noise exposure can bring on a state of overarousal, and performance suffers. These concepts are displayed graphically in Figure 28, from Broadbent (1971). Broadbent (1983) points out that the adverse effects of overarousal can be mitigated by factors that generally reduce arousal (such as sleep loss) and increased by factors that generally increase arousal (such as incentives and neuroticism).

Of course the picture is more complex than Figure 28 would indicate. As we have seen, performance in noise may be affected by other factors, such as circadian rhythm, personality, and psychological set. There is even some evidence that gender may be an additional determinant (Loeb et al., 1983). Consequently, Broadbent (1983) theorizes that there are actually two systems involved in arousal. The first system is the traditional concept, displayed in Figure 29, and the second takes the form of a monitoring system that attempts to compensate whenever arousal departs from an optimal level. If this second system operates properly, performance will not be adversely affected (Broadbent, 1983).

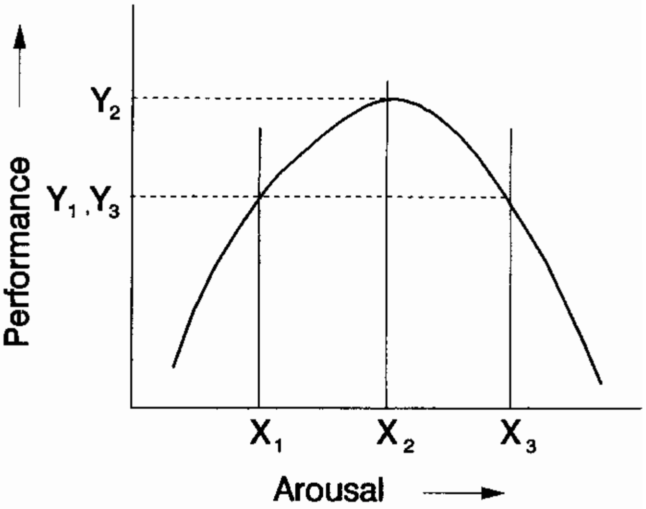

FIGURE 28. Changes in performance as a function of changes in arousal. A rise in arousal may give a rise in performance if it corresponds to a movement from X_1 to X_2; performance will rise from Y_1 to Y^2. But the same rise in arousal will give a fall in performance if arousal is already at X_2; a further rise to X_3 will give a drop from Y_2 to Y_3. (Broadbent, 1971. Reprinted by permission.)

Another popular theory used to explain the effects of noise on performance is Broadbent's "filter" theory (Broadbent, 1958, 1971). Broadbent (1971) describes the nervous system as a single channel, having a limited capacity for transmitting information. This limited capacity channel is preceded by a selective device or filter, which selects only certain stimuli for processing or storage. Noise causes the filtering of some stimuli in favor of others, usually those proceeding from dominant sources (as, for example, in the experiments of Hockey, 1970a, b; and Finkleman & Glass, 1970). This mechanism appears to be operating primarily in tasks involving perceptual selection, reaction time, and memory (Broadbent, 1971). Noise increases the tendency to select information from probable sources at the expense of information from probable sources at the expense of information from improbable sources, and in the extreme, evidence from only one source will be considered (Broadbent, 1971).

McGrath (1963) points out that Broadbent's filter has a bias in favor of novel stimuli and also those of greater physical intensity, a theory borne out by much of the evidence presented in this section. McGrath also refers to the arousal theory as an explanation for noise-induced performance decrements, and he conducted an experiment to test these two hypotheses. Subjects performed a perceptual selection task in which they detected increments in brightness of an intermittent light while listening to continuous, broadband noise at 72 dB, or a variety of auditory stimuli (music, TV, traffic noise, etc.). The results showed that the varied auditory stimuli enhanced performance more than the continuous noise. When the task was made more difficult by increasing the stimulus rate and shortening the interstimulus interval, performance was significantly better with the continuous, broadband noise. McGrath concludes that these results support a combined arousal-filter theory. The novel stimulus produced a beneficial effect at relatively low arousal levels, but a distracting effect at higher levels of arousal, once the task had been made more difficult. McGrath mentions that Broadbent (1958) also favors both theories in that the overall level of performance is determined by arousal, but the decline that often occurs as performance continues is caused by "increasing filter deviations."

In more recent years, Broadbent (1983) has developed another explanation for the effects of noise on performance, which involves a shift in the choice of strategies for task performance. He notes that noise will have a differential effect on two groups of people performing the same tasks in the same conditions, according to the way they choose to approach the task. Changes in strategy are particularly common to verbal tasks (such as verbal memory), but characterize nonverbal tasks as well. Noise appears to solidify a pre-existing strategy, so that once it has been adopted, it is more difficult to change (Broadbent, 1983).

Certain investigators, most notably Poulton (1976, 1977, 1978) disagree with Broadbent's theories. Loeb (1980) presents a succinct explanation of the controversy as follows: Poulton claims that many of the adverse effects attributed to noise exposure are not replicable. Increasing arousal can only benefit task performance, and any apparent degradations are due to the masking by noise of acoustic cues produced by the subject, which ordinarily provide feedback on the quality of performance (such as tapping sounds), or the masking of inner speech used for purposes of auditory memory or rehearsal. According to Loeb, Broadbent (1978) has replied that some of the studies cited by Poulton as failing to show adverse effects when feedback was eliminated did not use comparable noise levels. In addition, he believes that Poulton disqualified numerous studies for insufficient reason, and ignored other relevant studies, such as those concerning after effects. Loeb states,

> I think that Poulton has been of service in affirming the role that interference with acoustic feedback and various kinds of influence on short-term memory may play in influencing performance in noise, but I am not convinced that they play the role that he suggests in a great many of the cases cited (Loeb, 1980, p. 316).

Finally, it is important to note the contribution of psychological factors. Glass and Singer (1972) have demonstrated the importance of the predictability of the aversive stimulus, which they have determined is dependent upon the presence or absence of perceived control. Gulian (1973) stresses the role of noise-induced annoyance, which is related to aversion, anxiety, muscle tension, and so forth, all of which can affect task performance. Any theory of noise-induced performance effects would be incomplete without taking these effects into account.

4.9 SUMMARY

The preceding discussions provide confirmation for a variety of averse effects of noise on task performance, although the picture is rather complex. The effects on performance are not nearly as easily discerned and predictable as other noise effects, such as those on hearing or speech communication. As we have seen, the extent to which noise affects performance depends on numerous nonacoustical factors, such as the subject's biological and psychological state, as well as external factors, such as task complexity and the presence of other stressors. Comparison of research results is made more difficult by differences in approach and experimental design. These problems are then exacerbated by lack of control over possibly contaminating variables and lack of precise specification of the stimulus and other experimental conditions. Nevertheless, enough research has been conducted, presumably of sufficient quality, to enable us to make a number of useful generalizations.

4.9.1 Summary of Effects

Research on noise and vision suggests adverse effects on thresholds of sensitivity and CFF, but more research is needed with more explicit control of experimental conditions before positive statements can be made. There is fairly strong evidence for noise-induced shifts in perceived visual field resulting from noise bursts at 120–125 dB. Small but reliable effects of noise on vestibular function have been shown by a series of experiments using the Rail Task at Wright-Patterson Air Force Base. These effects are especially evident at an exposure level of 140 dB with hearing protectors (resulting in actual exposures substantially lower than this level), and are greater for asymmetric exposures. Motor performance usually adapts with repeated or prolonged exposure, but levels as high as 130–140 dB can show persistent decrements, even when hearing protectors are used. Most startle responses brought on by impulsive noise habituate with repeated exposure, but the eye blink response never habituates, and some amount of head movement rarely does.

Noise exposure level is, of course, one of the most important variables. Performance decrements generally begin to appear at levels around 95 dB, although noise below this level may cause adverse effects on particularly sensitive tasks. Continuous noise is less likely to be disruptive than intermittent noise. Aperiodic noise, probably because it is perceived as uncontrollable, is considerably more disruptive than periodically intermittent noise.

The effects of noise in combination with other stressors can be quite complex: synergistic, antagonistic, additive, or none. Noise usually has a beneficial effect when combined with sleep deprivation. Gender and circadian rhythm appear to interact with noise, but the direction of effects is unclear. Noise and incentive are both arousers, and noise may reduce the beneficial effects of incentive if overarousal should occur. Noise plus heat have produced mixed results: Sometimes noise has a beneficial effect on performance that has been degraded by heat, sometimes the effect is additive, and at times, synergistic. Personality factors interact with noise and level of arousal to affect performance in complex ways.

With respect to task variables, noise usually has little effect on simple tasks, and can even improve performance on monotonous tasks. Tasks requiring continuous performance, such as driving vehicles and flying planes, may be momentarily disrupted, especially in noise levels over 100 dB. These disruptions need not affect overall performance unless the task is quite demanding, but they may have serious effects if a high level of sustained performance is necessary to the job. Intellectual function is not usually affected unless the task is complex or unless a task must be performed continuously for long durations. Vigilance tasks are susceptible to noise exposure, especially when the signal to be watched for may originate from a large number of sources, one's internal criteria may not be cautious, or if the watch is long. Complex tasks, especially those involving more than one activity, are much more likely to be disrupted than simple tasks, with lower priority task components usually incurring the decrements.

It seems that noise can have even greater effects after exposure than during exposure and the most common effect appearing in the experimental literature is a reduced tolerance for frustration. Finally, even fairly moderate noise levels (80–90 dB) indicate that noise raises anxiety and increases the risk of hostile behavior, while decreasing the incidence of helpful behavior.

4.9.2 Discussion

Having looked at the various effects of noise on task performance found in the laboratory, the question remains as to how to generalize these results to real-life conditions. In fact, one might expect real-life effects to be either greater or less severe than those found in the laboratory. The chances are that they would be greater because most laboratory studies use acute exposures of fairly short duration. Consequently, adverse effects that tend to occur only with prolonged exposure, such as those characteristic of vigilance or continuous performance tasks, may not have time to show up, especially in more moderate levels of noise exposure. On the other hand, performance decrements in real-life conditions may be somewhat less than those found in laboratory experiments because noise-exposed workers and soldiers become familiar with both task and noise, thereby enhancing the process of habituation. The benefits of habituation, however, would disappear in emergency situations involving sudden changes in the task, especially if it should become unfamiliar, or the introduction of novel noise stimuli. Field studies should be helpful in elucidating this issue.

Another question that arises from studying the noise and performance literature is how to explain the apparently conflicting evidence. A good example would be the widely divergent results when noise is combined with heat. Most likely, these apparent conflicts are due to differences in experimental conditions, such as the relative magnitudes of the stressors and the type and difficulty of the task. Throughout the discussions we have seen considerable support for the "rule of inversion," with low and moderate stimulus levels enhancing performance and high levels causing degradations. But even when explanations are not readily apparent, it would be inappropriate to assume that the positive and negative results "cancel" each other. Although many investigations have failed to show significant adverse effects, the fact that many others *have* shown such effects indicates that these effects may very well be expected to occur in real life, but only in certain circumstances.

If indeed these adverse effects are most likely to occur in relatively high noise levels (above 95 dB, and especially above about 115 dB), perhaps we need not be overly concerned, because hearing protectors are usually required at these levels in industrial and military settings. Again, the assumption of safety is unwarranted. First, we have seen that performance decrements have occurred from high levels of noise exposure even though subjects wore hearing protection. Also, as explained above, real-life fitting and wearing practices greatly reduce the effectiveness of hearing protectors, especially ear plugs, and, unfortunately, many soldiers and industrial workers are unwilling to wear hearing protectors despite official requirements.

One might also say that the asymmetric exposure condition, which appears to be considerably more disruptive to task performance than the symmetric condition, is esoteric and not reflective of real life. It is true that individuals do not usually wear just one hearing protector. However, when one considers the uncertainty inherent in the field use of hearing protectors, it is quite conceivable that one plug could be fitted well and the other poorly. It is also conceivable that a noise-induced hearing loss could be greater in one ear than in the other, or that one ear canal could be occluded by cerumen and the other not. Thus, some degree of asymmetry could be relatively common.

Finally, assuming that adverse effects on performance are likely to occur, what are the consequences of these effects? Broadbent (1979) points out that in the typical laboratory study, the increase in errors is only about 1% of the correct responses, but that this represents an increase of 50% over the number of errors made in quiet. The importance of this increment depends entirely upon the context. If errors are not expensive, then there is no problem. But if accuracy is more important than speed, changes of this magnitude must be taken seriously (Broadbent, 1979). If both accuracy and speed are important, and if the consequences of errors are severe, then noise represents a serious hazard to task performance.

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Chapter 5

Conclusions and Research Recommendations

At the conclusion of a review such as this, it is apparent that a great deal of research has been done on communication and job performance in noise. Although this review may help to prevent unnecessary repetition, similar or repetitive research projects may be in progress at this time, and there may be some merit in these projects, since replication is often desirable. There are, however, some obvious information gaps, which, if filled, could be very beneficial to the end users—workers and their employers, soldiers and their commanders, and in the end, consumers and taxpayers. Some of these areas are logical starting points of coordinated research programs, but they are so underresearched that the related research and criteria have no authoritative base.

5.1 EFFECTS ON PERCEPTION OF SPEECH AND WARNING SIGNALS

5.1.1 Noise

One important information gap is the lack of knowledge of the speech communication requirements for various occupations. To assess the needs for communication systems and listeners' hearing sensitivity, it is necessary to have at least some knowledge of the type, amount, spectrum, dynamic range, content, and intelligibility of speech communication needed for the most efficient conduct of specific tasks. In most cases, little or nothing is known of these parameters.

For the most efficient allocation of resources, as well as for the protection of those involved, it would be useful to know the consequences of communication failures. Because many workers and servicemen are reluctant to complain about their working conditions, this information is not always easily gained. Perhaps the best approach would be a carefully worded survey of personnel working in high-noise environments, promising anonymity.

A worthwhile research area that has received very little attention in this country is the effect of high levels of vocal effort on the larynx and the incidence of vocal abnormalities and pathologies among individuals who communicate in high noise levels. A related topic would be the influence of vocal strain and vibration on speech intelligibility.

A final recommendation in this area would be an assessment of the adequacy of auditory warning signals, for use both in industry and in aviation, in view of the research and guidelines of Patterson and his colleagues, cited in Chapter 4.

5.1.2 Hearing Loss

As stated above, the most urgent need is to characterize the conditions in which individuals need to communicate and to assess the abilities of hearing-impaired personnel to recognize speech in these conditions, either through modelling or through actual testing. Only then should criteria be developed to exclude certain persons from job categories.

Another important project would be to continue the investigation of the ability of people with hearing impairment to detect and recognize warning sounds. The addition of the binaural listening mode, an assessment of signal recognition (in contrast to detection), and a population of subjects with hearing impairment would greatly strengthen the existing body of research.

5.1.3 Hearing Protectors

Hearing protectors are increasingly relied upon in American workplaces, often as a substitute for engineering controls, although this is not always the most desirable method of controlling the exposure. They are also quite often resisted by workers on the grounds of interfering with speech communication or the perception of warning signals, even though their supervisors usually counsel employees that no such adverse effects will occur. It would be useful to know more precisely the extent of user dissatisfaction because of speech communication and signal perception difficulties, as opposed to other factors, such as comfort and appearance, and under which conditions these difficulties are most likely to occur. This kind of information could be gained through the use of carefully worded, anonymous surveys.

Most hearing protectors are characterized by attenuation curves that slope toward the high frequencies, causing adverse effects on the perception of speech and warning signals, especially in people with hearing impairment. The work that has been initiated on hearing protectors with flat attenuation properties should be continued and expanded to achieve greater attenuation and lower costs. These devices need to be tested not only for speech recognition, but also for possible improvements in signal detection and localization, with subjects with normal hearing and subjects with hearing impairment. If the anticipated improvements are realized, this type of effort could stimulate the development and standardization of a mechanism for rating hearing protection with respect to speech communication and signal detection effects.

In addition, the continued development of practical, wearable, nonlinear devices should be encouraged, especially those using noise cancellation. There should be further testing of the physical properties of these devices, and efforts should be made to encourage quality control on the part of the manufacturers.

Well-designed and controlled research needs to be conducted on the effects of hearing protection on the perception of warning signals and machinery malfunction in sufficiently large populations of listeners with a range of hearing impairments. Also, the apparent differences between the effects of plugs and muffs on the perception of speech and warning signals need to be explored further. If such differences occur systematically, it would be useful to know whether they are due to spectral differences or to some other factor.

5.2 THE EFFECTS OF NOISE ON TASK PERFORMANCE

The effects of noise on task performance represents a very large literature. Because only a broad overview of the subject has been presented in this monograph, it has not been possible to evaluate all of the relevant studies in each area and to scrutinize each one. Thus, a more thorough perusal of the research in each area would be helpful. Perhaps the next step would be to select the particular area of greatest interest to the user (for example, the industrial or construction company, the military service, or the government agency, etc.), extend the effort to cover studies omitted in this section, and examine the experimental procedures of all of the relevant studies in some detail. This would enable the user to determine the most beneficial approach to any desired research effort.

Most research on the effects of noise on performance has taken place under laboratory conditions. Subject populations have generally consisted of college students with normal hearing, who are, presumably, highly motivated, interested in the experiment, and eager to please. To the extent that these qualities do not reflect the attitudes of industrial and military personnel, it would be useful to employ subjects similar to those who regularly perform in noisy conditions. In addition, experiments should be conducted in the field, whenever possible, using tasks that are representative of real jobs, such as driving noisy vehicles, manipulating aircraft controls, monitoring gauges, and sighting targets. Such tasks should be examined singly and in the combinations in which they actually occur, with and without the additional environmental stressors that often accompany the task, such as heat and vibration. Noise and task durations should reflect actual durations encountered in work situations.

It would also be useful to examine the effect of noise on performance with and without hearing protectors, and when hearing protectors are partially inserted, symmetrically and asymmetrically. Noise levels and spectra should reflect those regularly encountered in occupational situations.

Finally, because cooperation and adherence to orders are critical in many industrial and military environments, it would be useful to explore the effects of high levels of noise on social behavior specifically in these environments. Although designing realistic yet controlled conditions is difficult, the results could be of great interest and utility.

Appendix

Military Performance Criteria

All three military services now have hearing sensitivity criteria that restrict personnel from certain jobs and classes of jobs. In fact, the Department of Defense now has criteria for rejection for appointment, enlistment, and induction that apply to all three services (U.S. DoD, 1986). These criteria were issued as DoD Directive 6130.3 on March 31, 1986, and were adopted by the U.S. Army on July 27, 1986. They reflect a tightening of the previous Army induction standards in that they now include the 3000–Hz frequency, and they no longer allow unlimited hearing loss in the poorer ear. It is interesting to note, however, that they are generally less stringent than the levels identified by recent researchers as the point of beginning hearing handicap (see Robinson et al., 1984; Smoorenburg, 1982, 1986; and Suter, 1985). Table 8 specifies the acceptable hearing threshold levels for both ears.

U.S. Army

Until the DoD-wide directive, the U.S. Army has had its own induction standards, which have been somewhat more complex than the new standards (U.S. Army, 1983). Table 9 gives the Army's previous acceptable hearing threshold levels for appointment, enlistment, and induction from 1983.

The Army also has criteria for aviators and air traffic controllers (U.S. Army, 1987). These are somewhat more stringent than the induction criteria. They are shown in Table 10.

Soldiers may be denied appointment, enlistment, and induction for numerous otological abnormalities, such as severe external or middle ear otitis, mastoiditis, or history of ear surgery. Aviators may be declared unfit for flying according to another list of otological criteria, which includes abnormalities of labyrinthine function, eustachian tube dysfunction, and deformities of the pinna that would be likely to cause problems with the use of protective headgear for extended periods (U.S. Army, 1987).

The U.S. Army has a system of profiling hearing impairments to qualify current personnel for the performance of various duties. A profile designation of 1 indicates a high level of medical fitness. A 2 profile means that a person possesses some medical condition or defect that may impose limitations on classification and assignment. A 3 profile indicates that the medical condition requires certain restrictions, and the 4 profile drastically limits performance (U.S. Army, 1983). Table 11 shows H (hearing) profiles 1 through 4, according to Army Regulation 40-501 (U.S. Army, 1987).

According to AR 40-501 (U.S. Army, 1987), officers initially assigned to the Armor, Artillery, and Infantry branches, as well as to the Corps of Engineers, Military Intelligence, Military Police Corps, and Signal Corps, must qualify for the H-1 profile. However, their hearing may deteriorate and they may still be retained if they demonstrate continuing ability to perform their duties or if they are able to perform their duties with the help of a hearing aid. Other personnel may likewise be retained if they are capable of performing their duties effectively with a hearing aid. Their assignments may, however, be limited. Personnel may be declared unfit for duty during mobilization if they achieve an SRT greater than 30 dB while using a hearing aid.

The Army also lists requirements for specific military occupational specialties (MOS), which include hearing acuity. Each MOS has an H profile, sometimes with added requirements. For example, MOSs such as Air Traffic Control Radar Controller (93J), Area Intelligence Specialist (97C), and Interrogator (97E) "must be able to hear a wide range of human voice tones" (U.S. Army, 1986, p. 746). Infantrymen (11B) "must be able to hear oral commands in outdoor areas from distances up to 50 meters" (U.S. Army, 1986, p. 702). The majority of MOS classifications require the minimum of an H-2 profile. In jobs where communication and signal identification is particularly important, H-1 profiles are required. Examples of MOSs requiring H-1 profiles are:

Fire Support Specialist	13F
Cavalry Scout	19D
M48, M60, and M1 Armor Crewmen	19E and 19K
Multichannel Communications Equipment Operator	31M
Tactical Circuit Controller	31N
Wire Systems Operator	36M
Explosive Ordinance Disposal	55D
Physical Activities Specialist	03C

Surprisingly, certain other occupations are given H-2 profiles, despite the apparent need for good communication abilities. Examples:

Air Traffic Control Tower Operator	93H
Air Traffic Control Radar Controller	93J
Locomotive Operator	65B
Special Agent	95D

U.S. Air Force

The Air Force has its own set of H profiles, as shown in Table 12 (U.S. Air Force, 1987). The following jobs or activities are restricted to an H-1 profile:

Air Force Academy Admission
Flying Classes I and IA
Initial Flying Class III
Initial AFROTC Selection

Initial Selection for Missile Launch Crew
Initial Selection for Air Traffic Controller Duty
Other Personnel Initially Entering Potentially Noise Hazardous Career Fields
Other Personnel as Required

The H-2 profile is required for continuing in Flying Classes II and III, and the H-3 is required for reenlistment within 6 months of separation and for active duty personnel.

U.S. Navy

The Navy does not yet have a system of H profiles, although such a system has been proposed (Page, 1986). There are, however, criteria for the following positions and duties: qualifications for commission; appointment, enlistment, or induction; submarine duty; flight training; and Service Groups I, II, and III. These criteria are shown in Table 13 (U.S. Navy, 1980, 1984).

Other Military Criteria

According to Frohlich (1981), all German military pilots must have hearing sensitivity no worse than 30 dB between 250 and 2000 Hz. Candidates for flight training must have hearing threshold levels of 20 dB or better between 250 and 2000 Hz and at 3000, 4000, and 6000 Hz. The combined losses in both ears must not exceed 210 dB.

Gloudemans (1981) reports the results of a survey of military hearing threshold level criteria for several nations. He gives data for Italy, Portugal, Canada, Norway, France, the Netherlands, and the United States. These data appear to be somewhat unreliable, however, in that thresholds based on ANSI and ASA zero reference levels appear in the same table (unspecified), and the author gives criteria for the 5000 Hz frequency (attributed to the U.S. Army!).

Prevalence of Hearing Impairment in the U.S. Army

Walden, Prosek, and Worthington (1975) conducted a very large and thorough study of the prevalence of hearing loss within three high-risk (noisy) branches of the U.S. Army: infantry, armor, and artillery. The investigators randomly selected 1,000 subjects in each of three branches, including 200 in each of five length-of-experience categories. Tests of pure-tone hearing threshold levels, SRT, and speech recognition of CNC monosyllables in quiet (at 40 dB above SRT) were administered, and each subject was assigned the appropriate H profile. The results revealed no large differences in the prevalence of hearing loss among the three branches, but, significantly, they did show that 20–30% of the personnel in these branches have hearing losses resulting in H-2 profiles or worse. In the shortest time-in-service category (1.5–2.4 years), nearly 90% of the personnel carried an H-1 profile. In the longest category (17.5–22.4 years), however, only about 45% had an H-1 profile. Speech audiometry produced results that were within normal limits, although both SRT and monosyllable recognition scores in quiet deteriorated slightly with increasing years of service.

Table 8. Department of Defense hearing threshold level induction standards (DoD, 1986).

500–200 Hz	Average threshold no greater than 30 dB No single frequency greater than 35 dB
3000 Hz	No threshold greater than 45 dB
4000 Hz	No threshold greater than 55 dB

Walden and his colleagues also administered questionnaires to their 3,000 subjects in which each subject was asked to state his current H profile. Of the 1,702 men who knew their profiles, a substantial number of them did not report the appropriate profile. In some time-in-service categories, nearly one half of the subjects had worse profiles than they reported (Walden et al., 1975).

The questionnaires also contained items for self-reported hearing assessment, the responses to which remained anonymous. Of the 3,000 subjects, 49.7% (1,462) believed they had a hearing loss. Many of these respondents carried an H-1 profile, possibly indicating that this profile allows sufficient hearing loss to be noticeable to some individuals. Sixty-three percent of the 1,462 (31% of the total) felt that the hearing loss interfered with their ability to communicate, 44.3% of the 1,462 (22% of the total) reported that the hearing loss interfered with social functioning, and 37.4% of the 1,462 (18% of the total) reported that the hearing loss interfered with job performance. Interestingly, a progressively smaller number indicated difficulties with job performance as years of service increased, despite the fact that increasing service duration produces greater hearing loss. In contrast, the percentage of subjects who believed that the hearing loss interfered with social func-

Table 9. U.S. Army hearing threshold level standards for appointment, enlistment, and induction prior to the DoD directive (AR 40-501, 1983).

Frequency	*Both ears*
500 Hz 1000 Hz 2000 Hz 4000 Hz	Audiometer average level of 6 readings (3 per ear) at 500, 1000 and 2000 Hz not more than 30 dB, with no individual level greater than 35 dB at these frequencies, and level not more than 55 dB each ear at 4000 Hz; or audiometer level 30 dB at 500 Hz, 25 dB at 1000 and 2000 Hz, and 35 dB at 4000 Hz in the better ear.

OR

If the average of the three speech frequencies is greater than 30 dB ISO-ANSI, reevaluate the better ear only in accordance with the following table of acceptability:

Frequency	*Better ear*	
500 Hz	30 dB	Poorer ear may be deaf.
1000 Hz	25 dB	
2000 Hz	25 dB	
4000 Hz	35 dB	

TABLE 10. U.S. Army hearing threshold level standards for aviators and air traffice controllers (AR 40-501, 1987).

		Frequency (Hz)					
		500	*1000*	*2000*	*3000*	*4000*	*6000*
Classes 1 & 1A	Each ear	25 dB	25 dB	25 dB	35 dB	45 dB	45 dB
Class 2	Better ear	25 dB	25 dB	25 dB	35 dB	65 dB	75 dB
(Aviators)	Poorer ear	25 dB	35 dB	35 dB	45 dB	65 dB	75 dB
Class 2 (Air Traffic Controllers)	Each ear	25 dB	25 dB	25 dB	35 dB	65 dB	75 dB
Class 3	Better ear	25 dB	25 dB	25 dB	35 dB	65 dB	75 dB
	Poorer ear	25 dB	35 dB	35 dB	45 dB	65 dB	75 dB

tioning tended to increase with time in service. The authors suggest that soldiers with considerable time in service may be less willing to admit that their hearing impairment can affect their abilities to communicate and to perform their jobs adequately (Walden et al., 1975).

Consequences of Impaired Hearing in the Military

There is no doubt that the hearing impairments characterized by the H-2, H-3, and H-4 profiles can degrade speech communication. This is even true of the H-1 profile under certain conditions. To convey the extent of this effect, hypothetical hearing losses that typify the different H profiles are shown in Table 14 and plotted in Figure 29 (from Richards, 1973), which shows the relative intensities and frequencies of various speech components at a long-term rms (conversational) level of 60 dB. One can see that even with the H-1 profile, much of the consonant area, especially the high-frequency consonants, and some of the third and all of the fourth vowel formants are lost. The H-2 profile interferes with a larger portion of the speech spectrum, which includes all of the high-frequency consonants, and all of the fourth, most of the third, and some of the second vowel formants. Listeners with a typical H-3 profile will lose most consonants, most of the second vowel formant, and all formants above that.

In Figure 30, these typical H profiles have been plotted against the graph developed by Stevens and Davis (1938, 1983) (see Figure 11 in Chapter 2) showing the number of discriminable units in the auditory area. Kryter's (1984) curves for the mean and 90% of critical intensities during speech have been reproduced in the lower portion of the chart. Accordingly, one can see that the typical H-1 profile would miss approximately 37% of the discriminable units in the speech range. A person with an H-2 profile would lose about 50%, while the H-3 profile would cause nearly 80% of the speech range to be inaudible.

The reader should bear in mind that these estimates assume a conversational (60-dB) or "everyday" (65-dB) level of speech in quiet; conditions that are not always typical of

TABLE 11. U.S. Army physical profile for hearing (AR 40-501, 1987).

H-1	Audiometer average level for each ear not more than 25 dB at 500, 1000, 2000 Hz with no individual level greater than 30 dB. Not over 45 dB at 4000 Hz.
H-2	Audiometer average level of six readings (three per ear) at 500, 1000, 2000 Hz of not more than 30 dB, with no individual level greater than 35 dB at these frequencies, and level not more than 55 dB at 4000 Hz; or audiometer level 30 dB at 500 Hz, 25 dB at 1000 and 2000 Hz, and 35 dB at 4000 Hz in better ear. (Poorer ear may be deaf.)
H-3	Speech reception threshold in best ear not greater than 30 dB HL, measured with or without hearing aid; or, acute or chronic ear disease not falling below retention standard. Aided speech reception threshold measured at "comfort level," i.e., volume control of hearing aid adjusted to 50 dB HL speech noise.
H-4	Below standards contained in Chapter 3 [in *AR 40-501*, 15 July 1987]. Factors to be considered: Auditory sensitivity and organic disease of the ears.

TABLE 12. U.S. Air Force hearing threshold level profiles (AFR 160-43, 1987).

H-1	500 Hz	Must not exceed 25 dB, each ear
	1000 Hz	Must not exceed 25 dB, each ear
	2000 Hz	Must not exceed 25 dB, each ear
	3000 Hz 4000 Hz 6000 Hz	Sum of audiometric thresholds at these frequencies for both ears must not exceed a total of 270 dB.
H-2	Audiometric thresholds for the frequencies 500, 1000, or 2000 Hz may equal but not exceed the following:	

	500 Hz	1000 Hz	2000 Hz
Better Ear	30 dB	30 dB	30 dB
Worse Ear	30 dB	50 dB	50 dB

H-3	Any hearing loss greater than H-2. The patient's remaining auditory acuity, unaided or aided, must permit the reasonable fulfillment of the purpose of the individual's employment on active duty in some occupational capacity commensurate with his or her grade.
H-4	Any hearing loss with which, despite the maximum benefit from a hearing aid, the active duty member is unable to perform the duties of his or her office, grade, or rank in such a manner as to reasonably fulfill the purpose of his or her employment.

Table 13. U.S. Navy hearing threshold level standards (NAVMED 25 Nov. 1980 and 3 Aug. 1984).

Qualification for Commission (November 25, 1980)
Each ear:
Av. 500, 1000, 2000 Hz must not exceed 30 dB, no single frequency greater than 35 dB
3000 Hz–45 dB
4000 Hz–60 dB

Appointment, Enlistment, or Induction (November 25, 1980)
Each ear:
Av. 500, 1000, 2000 Hz must not exceed 30 dB, no single frequency greater than 35 dB
4000 Hz–55 dB

OR, if the average at 500, 1000, and 2000 Hz is greater than 30 dB, the better ear must not exceed:
500 Hz–30 dB
1000 Hz–25 dB
2000 Hz–25 dB
4000 Hz–35 dB
Poorer ear may be totally deaf.

Submarine Duty (August 3, 1984)
Same criteria as in qualification for commission, above.
Submarine ST personnel must also not exceed:
500 Hz–35 dB
1000 Hz–30 dB
2000 Hz–30 dB
4000 Hz–40 dB
8000 Hz–45 dB
If testing at 8000 Hz is impractical, 6000 Hz may be substituted, with a maximum of 40 dB, but excess loss at 6000 Hz may be disregarded if all other hearing criteria are met.

Service Groups I and II (August 3, 1984)
(Audiograms must be obtained on all flight physical exams.)
Hearing threshold levels must not exceed:

	Better ear	*Poorer ear*
500 Hz	35 dB	35 dB
1000 Hz	30 dB	50 dB
2000 Hz	30 dB	50 dB

Service Group III (August 3, 1984)
(Audiograms must be obtained on all personnel except for personnel aboard ship.)
In general, hearing threshold levels must not exceed:

	Better ear	*Poorer ear*
500 Hz	45 dB	No requirements
1000 Hz	40 dB	
2000 Hz	40 dB	

Individuals failing to meet these standards, but whose hearing, in the opinion of the examining physician, is commensurate with safety in flight, must be evaluated by the Naval Aviator's Speech Discrimination Test and must obtain a score of at least 70.

Standards for Flight Training Candidates (August 3, 1984)
Hearing threshold levels must not exceed:

	Better ear	*Poorer ear*
500 Hz	25 dB	25 dB
1000 Hz	25 dB	25 dB
2000 Hz	25 dB	25 dB
3000 Hz	45 dB	45 dB
4000 Hz	60 dB	60 dB

A series of three audiograms is necessary to disqualify a candidate.

military situations. Speech levels will be considerably higher in combat conditions, but so, of course, will noise levels. In addition, the estimates resulting from Figures 8 and 9 in Stevens and Davis (1938, 1983) are based on a filtering paradigm, and do not include the additional degradation resulting from the distortion component. Because the distortion component is particularly troublesome in high speech and noise levels, we can expect that the resulting degradation will more than offset the benefits of increased vocal effort in combat-type situations.

Although most of the 3,000 soldiers tested by Walden et al. (1975) showed speech recognition scores within normal limits, the authors concluded that the standard clinical tests in quiet were not good indicators of the communication handicap resulting from high-frequency hearing loss. They observed that most combat situations involve moderate-to-intense levels of noise. One might add that most real-life speech will not be as highly intelligible as the clinical samples, nor will the listener be given the courtesy of hearing it at exactly 40 dB above his SRT. Walden and his colleagues concluded that although soldiers can communicate fairly well under ideal conditions, their hearing losses may pose great difficulties in the typical combat environment. This is borne out by the statement of 18% of the 3,000 soldiers sampled that their hearing losses interfered with their ability to perform their jobs. The authors recommend that the clinical evaluation of Army troops include a test of speech recognition in noise. They also recommend that the Army conduct a "detailed study of the effects of hearing loss on communication ability and job performance in general," and that "this research should be oriented to the combat readiness of soldiers with noise-induced hearing loss" (p. 22). Finally, they noted that many soldiers do not carry the appropriate H profile, and recommend that the profile system be rigorously administered.

The study by Walden et al. (1975) indicates that many soldiers in the armor, infantry, and artillery branches need to be reassigned to duties requiring a more lenient profile. According to Aspinall and Wilson (1986), "Some hearing conservation officers have suggested that the combat and

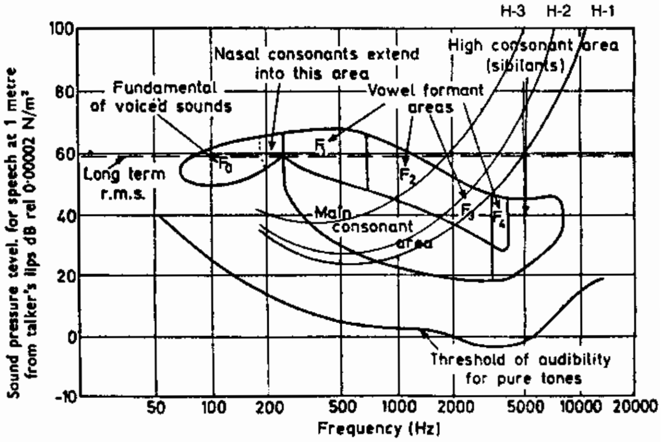

Figure 29. Relative intensities and frequencies of various speech components. (Richards, 1973. Reprinted by permission.) Typical U.S. Army "H" profiles are superimposed.

TABLE 14. Hearing threshold levels typical of Army "H" profiles.

		250	*500*	*1000*	*2000*	*3000*	*4000*	*6000 Hz*
H-1	HL	5	15	20	30	40	45	60
	SPL	29.5	26	26.5	38.5	47.5	54	68
H-2	HL	10	20	25	35	50	55	75
	SPL	34.5	31	31.5	43.5	57.5	64	83
H-3	HL	15	30	40	55	70	80	90
	SPL	39.5	41	46.5	63.5	77.5	89	98

combat support units would suffer a debilitating manpower shortage if all personnel were profiled according to their hearing loss along with the appropriate duty limitations" (p. 11). Clearly, the extent of hearing impairment in the Army, and perhaps in the military in general, poses a significant problem. The profiling system appears to be inadequate for effective communication on the job, and the system itself is poorly enforced. The situation merits increasing attention in the form of rigorous hearing conservation programs, a thorough study of the specific communication needs of each job to which personnel with hearing impairment are assigned, and the resulting revision of the profiling schemes.

Summary—Military Performance Criteria

The U.S. Department of Defense now has hearing threshold level standards for appointment, enlistment, and induc-

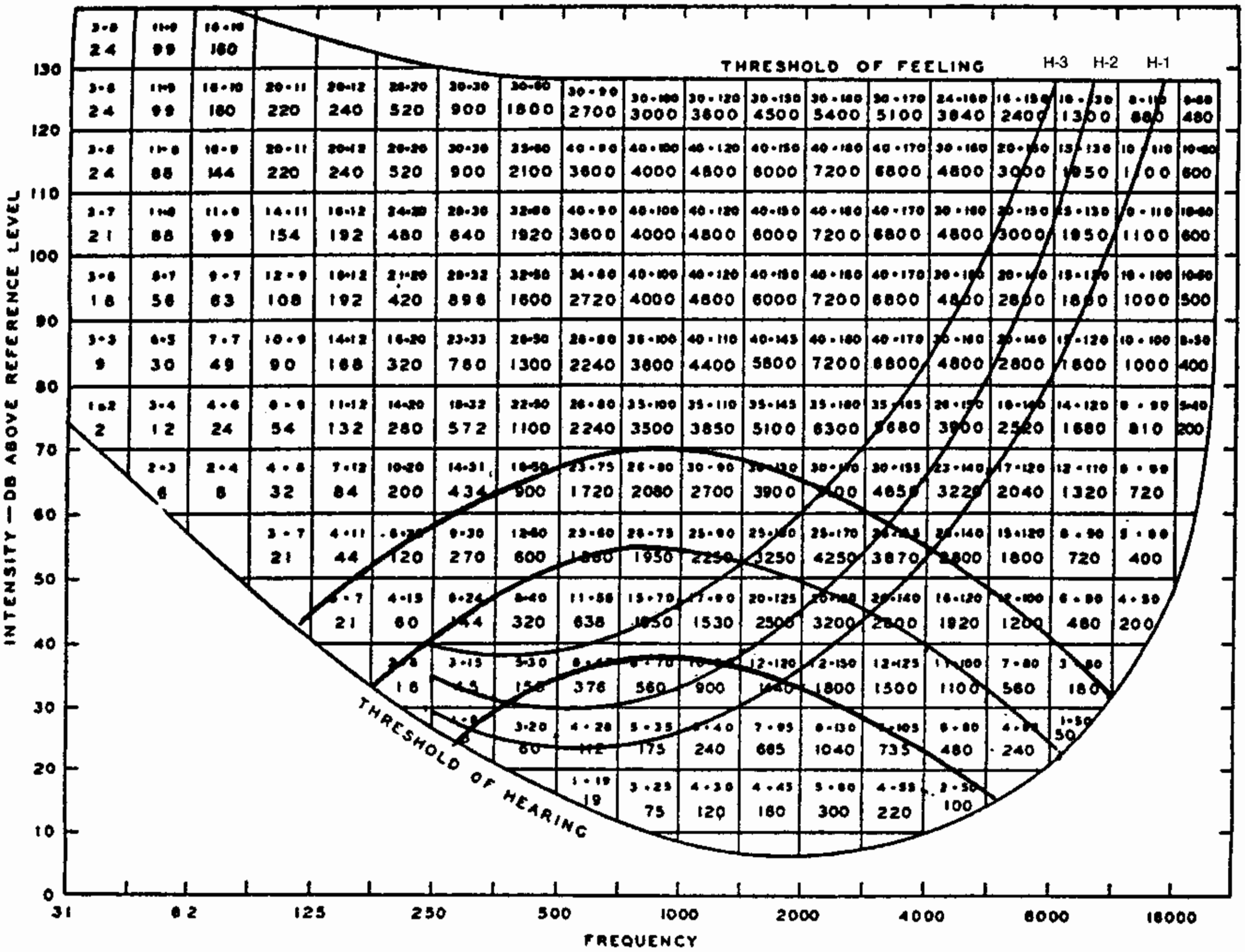

FIGURE 30. Typical U.S. Army "H" profiles plotted against the number of discriminable units in the speech area. (From Stevens and Davis, 1938 and 1983. Reprinted by permission). Kryter's (1984) curves for critical speech intensities have been added.

tion that apply to all three services. The U.S. Army has had its own set of induction standards that were in use until they were superseded by the DoD directive. The Army also has standards for admission to training as aviators, air traffic controllers, and drivers. In addition, it has a profiling system of H-1 through H-4, which applies to personnel within various military occupational specialties.

The U.S. Air Force also uses H profiles, which apply to the initial selection of candidates and the tenure of certain jobs, such as aviators, air traffic controllers, communication operators, and so forth. The U.S. Navy does not yet use H profiles, although a set of profiles has been proposed. The Navy does have hearing sensitivity criteria for positions and duties in which good hearing is considered important.

Most of the U.S. military standards for appointment, enlistment, induction, or even for jobs requiring significant amounts of communication are either at the upper limit or exceed the range identified by researchers as the point of beginning hearing handicap. This becomes a risky policy in circumstances in which human safety and mission success depend upon effective communication.

The German military system's criteria for flight training candidates and experienced pilots are slightly more stringent than those used by the U.S. Air Force. Hearing threshold level criteria also exist for other nations, but reliable data are not available at this time.

The prevalence of hearing handicap in the U.S. Army is very high, at least among soldiers in three high-risk branches: armor, artillery, and infantry. Many soldiers in these branches have profiles exceeding the H-1 designation, including over 65% of the soldiers in the most experienced category (17.5–22.4 years of service). Many soldiers do not carry the correct profile. Nearly one half of the soldiers in these branches believe they have a hearing impairment, and nearly one third of these report that the hearing impairment interferes with job performance. That these hearing impairments can impede job performance is not surprising, since many of them will exceed the range identified in recent research as the beginning of hearing handicap. The severity of the hearing loss problem in the U.S. Army, and very possibly in the military as a whole, is sufficient to be significantly disruptive of speech communication. The consequences of this disruption can be severe in terms of the destruction of costly equipment, and in extreme cases, the loss of life.

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