PSYCHOPHYSICAL INVESTIGATION OF THE REAL-EAR ATTENUATION OF HEARING PROTECTION DEVICES UNDER DIFFERENT SOUND-FIELD DIFFUSIVITY CONDITIONS

by

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(ABSTRACT)

Certain U. S. and international consensus standards governing hearing protection device (HPD) attenuation testing specify the use of a diffuse sound field to ensure the sound field remains uniform and random-incidence in an envelope about the subject's head (ANSI, 1974; ANSI, 1984; British BSI 5108:1983; Canadian CSA Z94.2-M1984; ISO 4869-1:1990; Swedish SS 882151). However, there are very few experimental data to support these restrictive requirements. The research presented herein investigated this issue by applying three different environments in tests of the attenuation of four different hearing protectors (three earmuffs and one earplug) at each of nine 1/3 octave band frequencies centered at 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz. One testing environment comprised a reverberant room with three loudspeakers, one firing in each room plane, that met all the specifications for testing under ANSI S3.19-1974 (ANSI, 1974). The other two environments progressively degraded the diffusivity of the sound field through the use of a single loudspeaker and room surface treatment with absorptive panels. A psychophysical real-ear-attenuation-at-threshold procedure was used to obtain attenuation data. The results showed small, but statistically significant, differences in attenuation among the three environments for specific test frequencies. Due to their statistical significance, these differences preclude direct comparison of attenuation data obtained in these different environments, especially when the data are used for purposes such as technical design research, product comparison and/or labeling, and testing standards development. However, being of small magnitude, these differences are not great enough to prevent obtaining an estimation of the attenuation that an individual is achieving with a particular device under these alternative environments. With this in mind, the use of an industrial audiometric test booth may be beneficial for determining an individual worker's protection levels actually achieved on the job. In sum, the interpretation of the results differs depending upon the intended purpose of the testing.

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INTRODUCTION

Background

The ability of people to hear sounds greatly enhances the quality of life. Most people depend on this ability for communication with others and the outside world. However, many occupational and leisure activities threaten to impair this gift. The Environmental Protection Agency (EPA) estimates that over nine million American workers are exposed to potentially damaging noise levels (EPA, 1981). In addition, many leisure activities, such as rock music concerts, target shooting, and vehicle racing, have been shown to produce levels of noise that can be damaging (Casali, 1990; Dresser, 1975; Johnson, 1987). The most common means of combating such noise is the use of hearing protection devices (HPDs). HPDs are worn on the head or in the ear canals of the individual and are designed to reduce the amount of airborne noise reaching the sensitive hearing mechanisms of the ear via the ear canal.

Relevant Terms

Concepts in HPD testing. Hearing protectors vary in shape, size, appearance, placement on the head, comfort, and protective effectiveness. When determining which protector to select, all of these attributes must be taken into consideration. One of the most important of these attributes is protective effectiveness, and the most common measure of a hearing protector's effectiveness is the noise attenuation that can be achieved with the device. Attenuation, however, does not have a precise acoustical definition, although it is widely used. Usually, when referring to HPDs, attenuation is implied to be synonymous with insertion loss. The insertion loss or noise reduction of an HPD are the terms generally used when it is necessary to be more precise. Insertion loss (IL) is the difference in the level of noise reaching the eardrum with and without the HPD donned. Thus, it requires two measurements at one position at two points in time. The noise reduction (NR) is the difference in the level of noise incident upon (outside) and transmitted through (inside) the HPD (Berger, 1986a). It requires simultaneous measurements with two microphones, one under and one outside the protector. (Formal definitions for each of the terms in this section appear in the Glossary.)

The most frequently used method of establishing attenuation is the real-ear attenuation at threshold (REAT). This method incorporates a psychophysical procedure aimed at determining a person's hearing threshold with and without the HPD donned, thus obtaining an occluded threshold and an unoccluded threshold, respectively. The unoccluded threshold is then subtracted from the occluded threshold to determine the attenuation of the HPD. This procedure is repeated for different frequencies to determine the HPD's effectiveness across a spectrum of one-third octave bands centered at 125 to 8000 Hz (hereafter termed frequency).

Before discussing the measurement of HPD attenuation in a sound field, several terms applied to sound field characteristics need explanation. Two major types of sound environments are addressed in this document: reverberant fields and free fields. The primary difference between them is the reverberation time, T_{60}, in the field. Reverberant fields have a reverberation time which is greater than zero, due to reflections from the walls, ceiling, and floor of the chamber. These cause the SPL to be more resistant to changes over distances from the sound source. True free fields, on the other hand, have a reverberation time which is zero or very nearly zero. The walls, ceiling, and floor, if present, absorb the sound energy incident upon them instead of reflecting it. (In fact, measurement of T_{60} in a free field is really only a "quasi-measurement" because there is theoretically no echo return of the sound past the measurement microphone.)

One use of reverberant and free fields is the production of diffuse (random-incidence) and directional fields. (For all practical purposes, a "random-incidence sound field" is synonymous with "diffuse sound field.") A diffuse field can be produced in either a reverberant or a free field, although it is much more difficult to create in a free field. On the other hand, directional fields, fields in which the majority of the sound energy at a point in space is from one direction, are more difficult to generate in reverberant fields. Highly directional fields, those in which the only sounds heard or measured are emanating directly from the source, can only be produced in a free field.

In addition to the two major types of sound fields, there are two major types of test chambers in which these sound fields are established: anechoic and reverberant chambers. Anechoic chambers simulate free fields through lining of the walls, ceiling, and floor surfaces with foam wedges designed to absorb the sound energy and reflect less than one percent of the sound energy incident on them. They are advantageous when measuring the sound power output of a device because the only sound measured in such an environment is the sound emanating directly from the source. In addition, their ability to generate highly directional sound fields is necessary when researching the effect that different angles of incident sound waves have on variables of interest. Furthermore, there is no lingering of sound waves when the source is turned off. Because there is no echo, as soon as the source is removed, so is the sound energy in the field.

Reverberant chambers are designed to simulate environments in which there are echoes, as with most real indoor and some outdoor environments. In such chambers, the sound at a point in space consists of the sound emanating from the source; the sound reflected from the walls, ceiling, and floor; and the sound reflected from other equipment in the room (Ostergaard, 1986). For testing HPDs to be used in industrial buildings that have reflective wall surfaces, as most typically do, reverberant rooms offer some face validity. Also, reverberant rooms are more common and generally less expensive than anechoic chambers.

HPD testing standards. Three standards have been adopted by the American National Standards Institute (ANSI) and the Acoustical Society of America (ASA) to establish a definitive procedure under which REAT values can be obtained. The first standard, ANSI Z24.22-1957, presenting pure tones through a single loudspeaker located directly in front of a subject seated in an anechoic chamber. This arrangement results in a highly directional sound field because signals emanate from a single source in a free field (ANSI, 1957).

The second standard, ANSI S3.19-1974, specifies presenting one-third octave band noises through three loudspeakers in a reverberant room, resulting in a diffuse sound field (ANSI, 1974). The Canadian CSA Z94.2-M1984 specifies very similar sound field requirements. The third standard, ANSI S12.6-1984, also specifies one-third octave band noises and a diffuse sound field, but does not require a certain number of loudspeakers nor does it specify the use of an anechoic or a reverberant chamber (ANSI, 1984). Thus, the emphasis of the ANSI S12.6-1984 standard is on the need for a diffuse sound field, which is generally established through the use of multiple loudspeakers, and allows the type of chamber in which that field is established to vary. British BSI 5108:1983, ISO (International Organization of

Standards) 4869-1:1990, and Swedish SS 882151 also allow the use of either type of chamber.

Issues in the Proposed Study

Presently, an ANSI Working Group, S12/WG11, is reviewing and potentially will update the current U. S. standard and an international group is reviewing and may change the current ISO standard. As a result, research studies are needed to support proposed updates to the requirements and to suggest improvements in the new standards. The results of such studies can have a significant effect on the revision of the standard and the testing and evaluation of hearing protectors in the future. This study proposes to explore several possible improvements that the committee is not currently addressing, but perhaps should be (J. G. Casali, personal communication, March 1, 1991). In addition, this study proposes to provide empirical evidence that will aid in the revision and improvement of the standard.

The main focus of this research is investigating the need for a diffuse sound field in REAT testing. Perhaps the diffusivity can be relaxed without significantly affecting the mean attenuation values obtained or resulting in an interaction effect with the type of hearing protector. If found acceptable for testing, the number of laboratories able to conduct this REAT testing may increase, due to the reduction in equipment cost and procedural difficulty of complying with the standard. For instance, if a uniform sound field is not required, the cost of specialized reverberant or anechoic chambers and the length and cost of test procedures aimed at verifying compliance may be reduced. Additional laboratories might then be able to implement the standard. (Currently only three laboratories in America outside the U. S. Government are known to meet the standard: Cabot Safety [Indianapolis], Paul Michael and Associates [State College, PA], and Virginia Polytechnic Institute and State University [VPI & SU, Blacksburg, VA]. Only VPI & SU has been certified by the National Institute for Standards and Technology for both ANSI S3.19-1974 and ANSI S12.6-1984 testing.)

Another possible benefit is that in-plant facilities would be better able to perform studies on-site for determining the protection levels that workers are actually receiving in the industrial environment. Park and Casali (in press[a]) have shown that the protection realized in the workplace is far less (many times, half or lower) than the manufacturer's rating (the Noise Reduction Rating [NRR] value). Thus, hearing conservation programs across the country could be greatly improved by providing a much more accurate assessment of workers' noise exposure while on the job. Yet, given all these potential benefits, no studies have been performed to determine if a uniform, diffuse sound field is necessary. This study proposes to explore this issue. If no significant difference in attenuation predicted by the REAT method is shown to exist when the sound field is changed, the aforementioned benefits may possibly be realized in the future. If a significant difference is shown to exist, the current restrictions will be supported through experimental data. Given the need to study these variables, a review of the pertinent literature and previous related studies follows.

HEARING AND THE EFFECTS OF SOUND AND NOISE

Sound and Noise

The difference between sound and noise is often confused. For the purpose of this document, sound is defined as a physical variation in a medium having mass and elasticity, which is capable of being heard by a human. Noise, on the other hand, is unwanted sound, or sound of a random nature. It can be steady, unsteady, or impulsive (ANSI, 1973). The human ear sensory organ is incapable of distinguishing sound from noise, but higher-order nerve centers afford interpretation of the nature of the sound or noise stimuli. Because either sound or noise has the ability to damage hearing, no distinction will be made between the two in this document.

Anatomy of the Ear

The normal, healthy human ear detects pressure oscillations which, through a complex sequence of events, stimulate the nerve hair cells that transmit sensory information to the brain. The ear is divided into three sections: the outer, middle, and inner ears. The outer ear consists mainly of the pinna (Figure 1) and the auditory canal (ear canal). The role of the pinna is to collect the sound and funnel it into the ear canal which, in turn, directs the sound to the tympanic membrane (eardrum). As they perform these tasks, the pinna and ear canal modify the acoustic wave, amplifying some frequencies and attenuating others.

The middle ear converts the modified acoustic wave to structural vibration of the eardrum, ossicles (three small bones: the malleus, incus, and stapes), and oval window. The inner ear converts this structural vibration to fluid motion in the cochlea (Figure 1). This motion stimulates neural hair cells that transmit the acoustic information to the brain through the auditory nerve (Ward, 1986). The above process is described as the air conduction of sound. The collection and modification of acoustical waves by the pinna and auditory canal are of primary concern when researching the effects of directional versus diffuse sound fields. Therefore, this process is explained in detail.

Whenever sound waves are collected and funneled into and along a tube, those sound waves will be modified. Such is the effect of the pinna and auditory canal. First, the particular shape and dimensions of the pinna cause certain frequencies of the incident sound waves to be amplified or

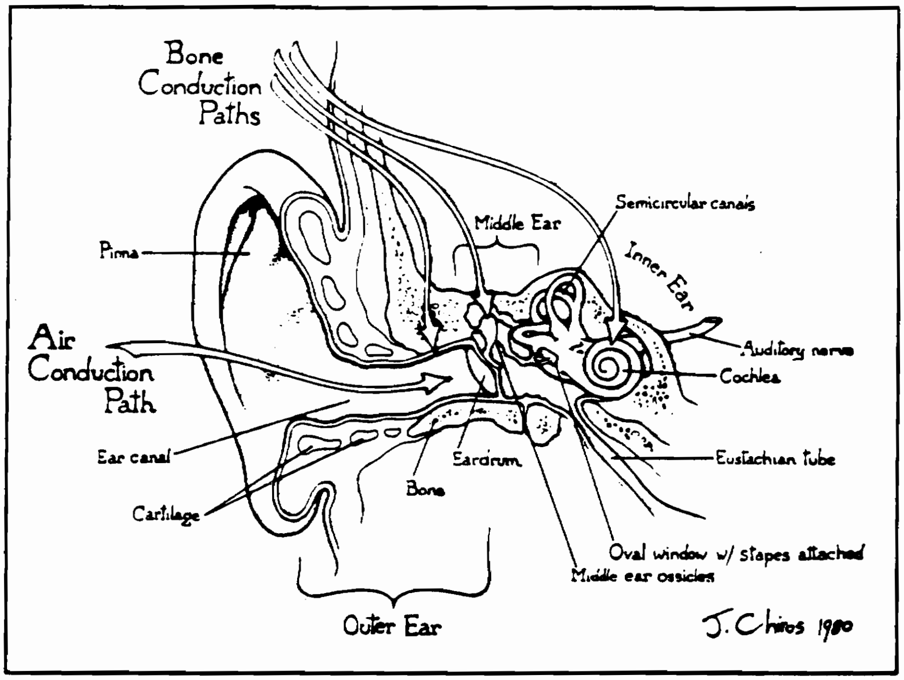


Figure 1. Basic anatomy of the ear and sound paths (adapted from Berger, 1980)

attenuated. Due to individual anatomical differences, the exact frequencies and level of amplification or attenuation are different for every pinna. The auditory canal, by virtue of its own shape and length, modifies the incoming sound wave even further (Ward, 1986). It has been shown to amplify sound in the frequency region of 3000 Hz, due to the wavelengths of these frequencies being approximately four times the length of the canal (Wiener and Ross, 1946). In general, the net effect of the head, pinna, and auditory canal is an amplification of 10 to 15 decibels (dB) of the sound in the frequency region of 2000 to 4000 Hz (Ward, 1986).

The modification of the sound source by the head and outer ear depends not only upon frequency, but also on the direction of the sound source. Shaw (1974) developed a family of curves (to be discussed later in detail) based on data from 12 different studies which show the transformation of sound pressure level from the free field to the eardrum in the horizontal plane and its dependence on azimuth (angle) and frequency. These curves show the difference the direction of the sound source has on the sound pressure level (SPL) at the eardrum as a function of direction and frequency, and the difference between the SPL at the eardrum and the SPL at the head center position as a function of direction and frequency.

The head and outer ear are also used to locate sound sources. It has been shown, for example, that simply by taping the pinna flat against the head, complete loss of monaural (one ear) localization of sound occurs (Roffler and Butler, 1968). Also, Fisher and Freedman (1968) found that binaural localization in the absence of head movement is better with pinnae and suggest that pinnae are the crucial factor under such conditions. When head movement is allowed, interaural difference cues aid in localization (Wallach, 1940). It has been shown that for low frequencies (below 1000 Hz), the difference in the phase (arrival time) of the sound incident upon the eardrum between the two ears provides localization cues. However, for high frequencies (above 4000 Hz), the difference in intensity between the two ears provides localization cues. Between 1000 and 4000 Hz, the localization ability decreases, suggesting that these two cues do not overlap well (Rossing, 1990).

Sound Paths

There are two main paths by which sound can travel to induce the sensation of hearing. The first is called the air-conduction path (Figure 1), described above. The second is the bone-conduction path. In bone conduction, the incident sound travels through the skull of the individual and vibrates the eardrum, ossicles, and/or the cochlea itself. Bone-conducted sound can bypass completely the pinna and ear canal. The threshold of bone conduction is approximately 40-50 dB higher than the threshold of air conduction, depending on frequency (Berger, 1986b).

Auditory Effects of Noise

Conductive and sensory hearing loss.

There are two main ways in which noise can damage the ear and result in a loss in hearing sensitivity. One, the conductive mechanisms of the ear (i.e., tympanic membrane, ossicles) can be injured, thus impairing the structurally borne transmission of sound to the nerve hair cells. Examples of conductive damage include rupture or scarring of the eardrum, dislocation of the ossicular chain, and rupture of the oval window. Conductive hearing losses are often the result of a single traumatic experience, such as a loud explosion or a blow to the head. They can also be occupationally induced, although such is rare. Conductive losses are sometimes recoverable through either surgical means or hearing aids.

Exposure to noise, the second way, can also cause hearing loss through dislodging or fatiguing sensory nerve cells (hair cells) so that they no longer function or are no longer as sensitive. Sensory hearing losses are irreversible by current medical means and are often the result of auditory abuse, such as the immediate acoustic trauma of a high-intensity auditory event or the cumulative effects of prolonged exposure to a high-level noise. Surgical procedures and hearing aids offer little relief from this disorder, which is the most common type of hearing loss due to occupational noises (Ward, 1986).

Temporary and permanent threshold shift. Either one or two types of hearing loss may result from auditory abuse. Hearing loss is characterized by a shift in a person's threshold level, increasing the level of noise necessary for that person to hear a signal. The first type of hearing loss is termed temporary threshold shift (TTS), characterized by a shift in the person's threshold to a higher level. It is called temporary because the amount of hearing loss is recoverable over time. Typically, TTS is determined by measuring a person's threshold two minutes after exposure and subtracting from that the pre-exposure threshold. The result is termed TTS_2. The amount of shift is dependent upon the frequency, intensity, and duration of the noise (Ward, 1976).

The second type of hearing loss is termed permanent threshold shift (PTS). It is also characterized by a shift in a person's threshold to a higher level, as with TTS. But PTS is permanent, as hearing sensitivity will not recover over time. One factor that has been shown to induce PTS is overexposure to noise, termed noise-induced hearing loss (NIHL). PTS and NIHL are often occupationally induced, due to the noise in the workplace. In fact, more people suffer from NIHL than all other occupational diseases combined (Miller, 1978). In addition, because NIHL is typically insidious, it is very dangerous and common, often going unnoticed until it is too late (Casali, 1986). Furthermore, it could become the most expensive major medical-legal concern confronting industry if the current trend continues (Shipley, 1985).

HEARING PROTECTION DEVICES

The use of HPDs is the most common means of reducing excessive noise exposure. They are designed to reduce the amount of noise incident upon the eardrum by obstructing the airborne path of that noise. There are three common types of HPDs: earmuffs, canal caps, and earplugs. Each is characterized by the location of its placement along the sound path. Earmuffs are designed to enclose the pinnae, thus obstructing noise from reaching the pinnae and ear canals, while canal caps are designed to seal the ear canals at their entrance, inhibiting the noise from entering them and exciting the eardrums. Earplugs are designed to fit inside the ear canals and seal them along their axes by contacting the canal walls. These three types of HPDs are discussed individually in further detail.

Earmuffs

Earmuffs are normally comprised of two circumaural earcups that enclose the pinnae and form a seal around them with foam- or fluid-filled cushions (Figure 2). The earcups are joined by a headband which can pass over the head, behind the head, or under the chin, and may be adjustable to

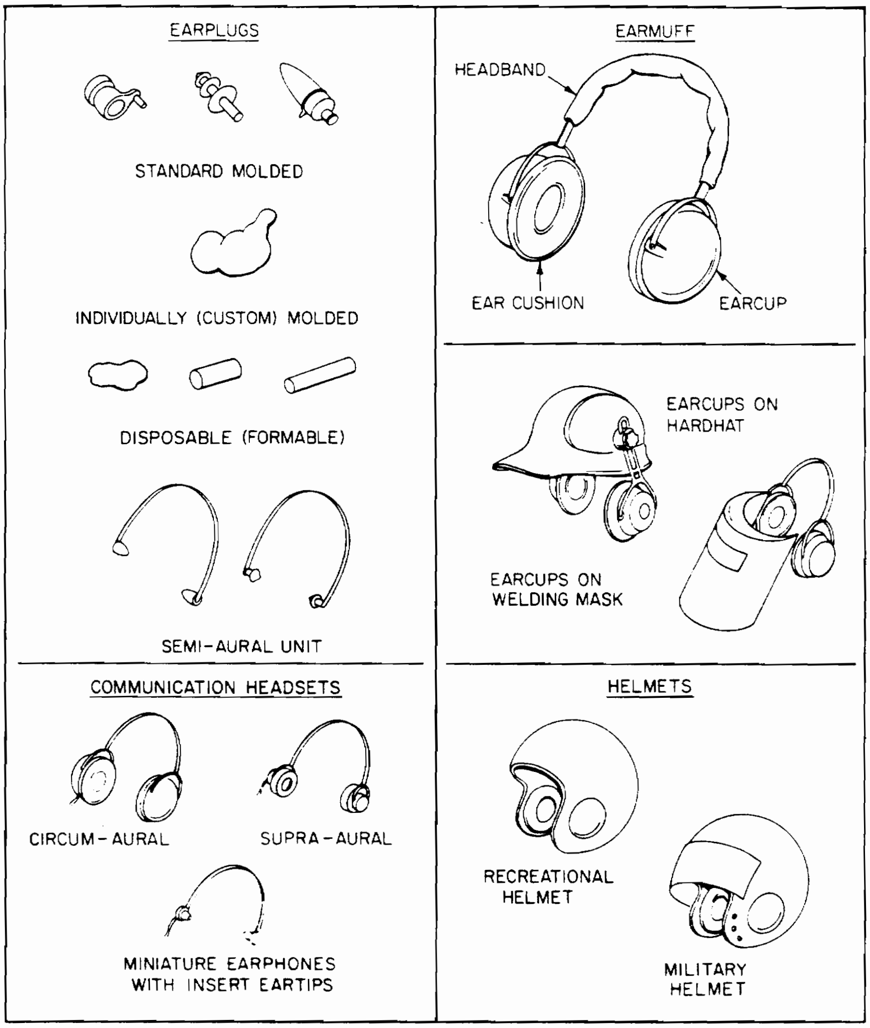


Figure 2. Types of hearing protection devices (adapted from Nixon, 1979).

accommodate different head sizes. This headband applies a force that aids in securing the device on the head and in forming an airtight seal around the pinnae. Earmuffs are supposedly designed such that one size fits nearly everyone. However, people with particularly large pinnae, extremely large or small heads, prominent cheek bones, or severe facial depressions may be difficult to fit properly.

Earmuffs are available in multiple sizes and shapes. They can differ in volume entrapped within the earcup, material composition and shape of the earcup, type of cushion, and compression force of the headband. These variables affect the attenuation, comfort, seal (place of air leaks, if any), and resonant frequency of the earcup. Between 125 and 1000 Hz, there is limited evidence that larger-volume earmuffs may provide better attenuation than smaller-volume earmuffs. However, for frequencies above 2000 Hz, smaller-volume earmuffs tend to provide better attenuation because they are less susceptible to vibrational modes within the earcup that reduce the ability to block high-frequency noises (Berger, 1986b).

The dimensions of the earcup opening for the pinna can also affect attenuation. In general, the smaller the cup opening, the greater the attenuation (Zwislocki, 1957). Compression force of the headband also has been shown to affect attenuation, the larger force providing better protection. However, the type of cushion, fluid- versus foam-filled, has been shown to have only a minimal effect on attenuation. Fluid-filled cushions provide slightly better attenuation at the low frequencies, with foam-filled cushions being slightly better at high frequencies (Casali and Grenell, 1989).

Earmuffs are particularly applicable for intermittent use, since they are easily donned and doffed. They offer hygiene advantages because they are not inserted into the ear canal. However, for extended use, they have been found to be hot, bulky, heavy, and uncomfortable. Eyeglasses, long hair, and caps tend to degrade attenuation (Berger, 1986b). Furthermore, they are subject to modifications by the user, such as drilling holes in the outer shell to aid ventilation or to personalize the device (Gasaway, 1984).

Canal Caps

Canal caps consist of small inserts that seal the ear canals at their entrance and protrude slightly into them (Figure 2). The headband connects the inserts and is usually not adjustable, has a low compression force, and is much smaller than that of earmuffs. Canal caps are designed to fit nearly everyone and offer many advantages for intermittent use because they are easily donned, doffed, and stored around the neck when not in use. However, some canal caps become quite uncomfortable when worn for extended periods (Park and Casali, in press[b]).

Earplugs

Overview. Earplugs are generally composed of wax, mineral fiber, rubber, vinyl, foam, silicone, or some other material having high sound transmission loss characteristics. As mentioned previously, earplugs are inserted into the ear canal where they form a seal with the ear canal walls. Some varieties afford very good protection against high-intensity noise, but this protection has been shown to be very dependent upon proper fit (Casali and Epps, 1986), since the plug-to-canal wall seal is critical. In addition, earplugs are generally comfortable in hot environments and do not interfere with eyeglasses or other safety equipment. There are three types of earplugs: premolded, user-molded, and custom-molded.

Premolded earplugs. Premolded earplugs, composed of vinyl, rubber, or silicone, are mass-produced in a preformed shape and inserted into the ear canal without prior molding or changing of that shape (Figure 2). They are generally characterized by one or more flanges extending beyond the core of the device, and some varieties are supplied in different sizes to accommodate a wide range of ear canals. This need for different sizes introduces problems. Choosing the correct size for an individual is very important and requires training and specialized knowledge. An improper size choice often results in a compromised fit and thus a reduction in protection or comfort. Requiring this choice to be made allows the possibility for it to be made incorrectly.

User-molded earplugs. User-molded earplugs are generally supplied in only one size and are molded by the user prior to insertion (Figure 2). Upon insertion, these devices are intended to conform to the shape of the ear canal. They offer other advantages by not requiring a selection of size or maintenance of a diverse inventory. However, because the user must form the plug prior to insertion, that person's hands must be relatively clean, thus complicating their use in certain environments (Berger, 1986b).

Custom-molded earplugs. Custom-molded earplugs are essentially a mold of a person's ear canal (Figure 2). In general, the procedure for obtaining a custom-molded earplug requires first having an impression made of the ear canal by an expert in the process. That impression must then be sent to a laboratory where a negative mold is made and a positive mold of a new material formed from it (Casali and Mauney, 1990). The resulting positive mold becomes the earplug, custom-fit for that individual. The effectiveness of this plug is highly dependent upon the skill of the individual taking the original impression, introducing a great deal of variability to the process (M. D. MacAllister, personal communication, August 22, 1990). However, because they are "customized," they can be used to motivate employees to wear their HPDs (Berger, 1986b).

Occluded Ear Sound Paths

When the ear is occluded by an HPD, there are four main paths by which sound can travel to induce the sensation of hearing (Figure 3). (1) The sound can travel through leaks in the protector. The protector itself may have holes in it through which sound can travel. Or the protector may not make a perfect seal against the head or ear, allowing sound to leak through these openings. (2) The protector itself may allow the transmission of sound through it, due to the material being an imperfect sound reflector. (3) The sound

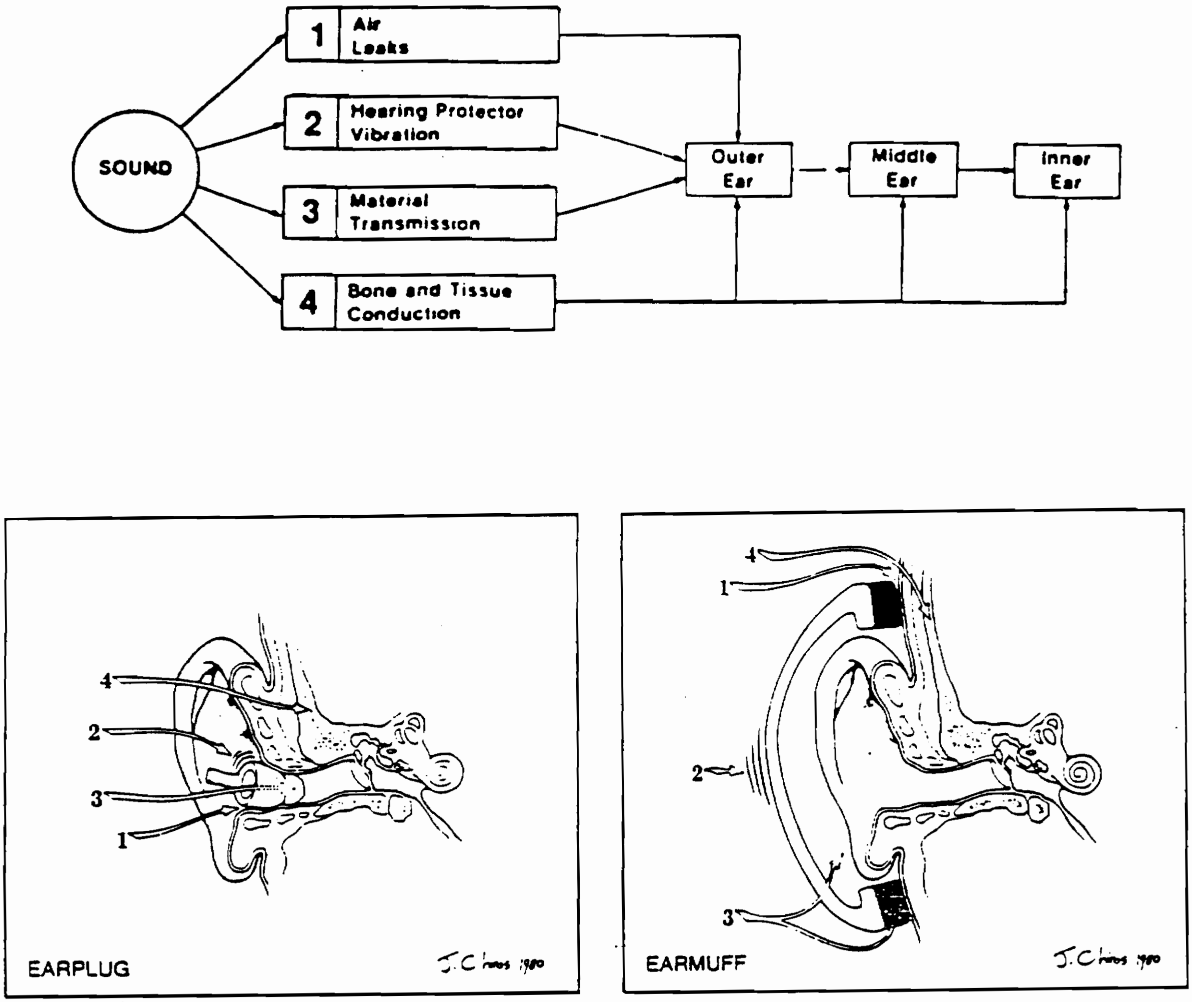


Figure 3. Occluded ear sound paths (adapted from Berger, 1986b).

may vibrate the protector, thus resulting in the protector becoming a sound source itself. (4) Sound can travel by bone conduction around the protector, as described earlier (Berger, 1986b; Botsford, 1972).

HPD ATTENUATION MEASUREMENT TECHNIQUES

Objective Techniques

Objective techniques are the most commonly used techniques when measuring the attenuation of hearing protectors. Some types involve physical measurement of sound pressure levels outside and inside the hearing protector (noise reduction), or with and without the protector (insertion loss) to determine the attenuation afforded by the HPD. Unfortunately, an accurate manikin of the human ear and head does not exist that can be used for this test (especially troublesome is the human flesh and bone conduction), and the validity of existing physical techniques using human subjects is questionable (Bolka, 1972). In fact, ANSI S3.19-1974 provides a method for physical measurement using a manikin head but states, it ". . . is intended for production test and engineering design; it is not suitable for earplug testing" (ANSI, 1974, p. iii). Therefore, other types of objective techniques have become the focus of attention to obtain reliable measures for standardization.

Another type of "objective" technique uses human subjects and psychophysical methods to compare the hearing threshold level differences between the occluded state and the unoccluded state. Nixon (1982) and Berger (1986a) provided overviews of the many techniques which have been proposed for the subjective evaluation of hearing protector attenuation. Berger and Kerivan (1983) described the advantages and disadvantages of some of these techniques and the features that have inhibited them from becoming standardized. Of these, one technique has emerged and become the most common method for measuring HPD attenuation. That technique, called REAT, has been standardized in international (ISO) and U. S. (ANSI) standards. Therefore, the remainder of this literature review is concerned with issues involving the use of the REAT technique for the measurement of hearing protector attenuation.

REAT and ANSI Standards

History. ANSI adopted the REAT technique for evaluating hearing protector attenuation in three different standards: ANSI Z24.22-1957, ANSI S3.19-1974, and ANSI S12.6-1984. The first standard, ANSI Z24.22-1957, involved the testing of hearing protectors using pure tones in a free-field environment, specifying a highly directional sound field with a one-loudspeaker sound source oriented directly at and in front of the subject (ANSI, 1957).

This standard received much criticism because it was felt that a highly directional sound field consisting of pure-tone stimuli was not representative of the environment or the type of sounds with which HPDs would be used. In addition, it was shown that earmuff attenuation can vary by as much as 15 dB as the angles of incidence (the angle at which the loudspeaker axis of immission strikes the HPD, relative to the horizontal head position) in highly directional sound fields vary. Furthermore, small differences in frequencies can cause large differences in attenuation due to resonances, and testing with pure tones at octave band centers would not reflect this difference (Berger, 1979). For these and other reasons, the standard was reviewed and updated.

In 1974 a new ANSI standard (ANSI S3.19-1974) replaced the 1957 standard and remedied some of the problems associated with that standard. It specified using one-third octave bands of noise in a reverberant environment with a diffuse sound field generated by three loudspeakers, each one directing its axis of immission toward a different plane of the room (ANSI, 1974). With these improvements, the EPA adopted the ANSI S3.19-1974 standard to be used in obtaining attenuation data for its product labeling regulations (EPA, 1990). However, the standard's instrumentation and measurement details tended to be open to user interpretation. The resultant interpretation differences led to high interlaboratory variability (Berger, 1985a).

In 1984 a third ANSI standard (ANSI S12.6-1984) replaced the previous two standards. It addressed many of the instrumentation and measurement details and was expected to reduce interlaboratory variability. Berger (1985a) discussed these particular details and presented some of the major similarities and differences among the standards. For instance, the S12.6 standard does not specify the type of sound field to be used for attenuation testing. It only states that the reverberation time in the space must be less than 1.6 seconds and that the field must be random incidence. Surprisingly, this standard was never adopted by the EPA and incorporated into the Code of Federal Regulations. Today, only the "old" S3.19 standard can be used for product labeling. However, ANSI still supports the newest standard, S12.6.

The restrictions these standards place on the sound field characteristics have important practical implications, as described earlier. A complete review of the issues pertaining to sound field directionality and its effects on hearing thresholds, both with and without hearing protectors, follows.

SOUND FIELD CHARACTERISTICS

Diffuse Sound Fields

Kuhn (1979) measured the SPL transformation from a diffuse field to the eardrum. The measurements were made on a manikin with six different-sized pinnae and a microphone placed at the location of the eardrum, thus simulating an acoustically average person. The six pinnae were chosen to reflect the range of pinna sizes, not to establish a mean. A one-third octave bandwidth white noise was used for the sound pressure measurements. For frequencies below 1000 Hz, a single standard pinna that was supplied with the manikin was used because different-sized pinnae appear to make little difference in this region. For frequencies above 1000 Hz, all six pinnae were used. The results of the experiment are shown in Figure 4 (Kuhn, 1979).

From the data, Kuhn (1979) noted a slight gain in SPL with an increase in frequency up to 630 Hz. For the frequencies between 630 Hz and 6000 Hz, the resonances of the ear canal and pinna primarily dictated the results, showing a large gain of about 15 dB at approximately 2700 Hz. Between 6000 Hz and 10000 Hz, the size of the pinna varied inversely with the SPL at the "eardrum."

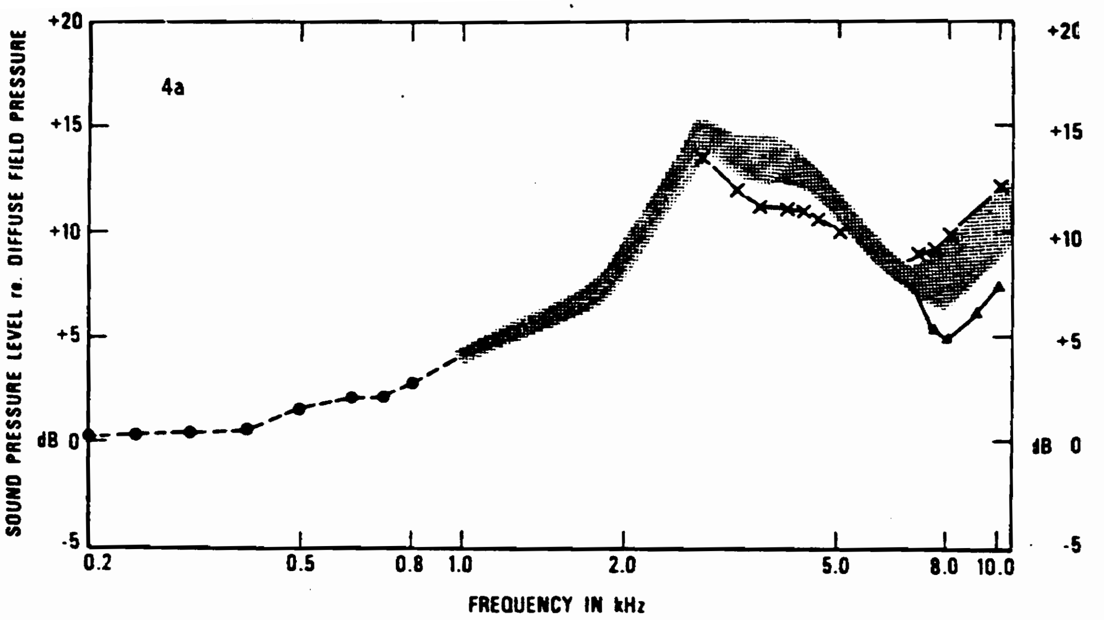


Figure 4. Sound pressure level measurements from a diffuse field to the eardrum taken on a manikin. Shaded area represents the range of the measurements using five pinnae, except for one of the two smallest pinnae and the largest pinna (adapted from Kuhn, 1979).

Killion (1979) measured the transformation of SPL in a random-incidence sound field in a reverberant room on a KEMAR (Knowles Electronics Manikin for Acoustic Research) manikin. The results, shown in Figure 5, represent the average of several measurements (Killion, 1979). These results appear to be in close agreement with those obtained by Kuhn (1979).

These curves represent a baseline which shows the ear's basic response to sound which is equal in energy across all frequencies and nondirectional in nature. They can be compared to the curves that are presented in the next section to isolate the effect of a specific frequency and/or angle of incidence.

Directionality Effects on the Unoccluded Ear

Point source directionality.

The threshold of hearing has been shown to vary in a directional sound field, not only with frequency but also with angle of incidence. Shaw (1974) combined 12 studies to develop two families of curves that show the transformation of the SPL from a directional, horizontal point source in a free field to the eardrum and that demonstrate the transformation's dependence on azimuth (angle) and frequency. Two types of measurements were made

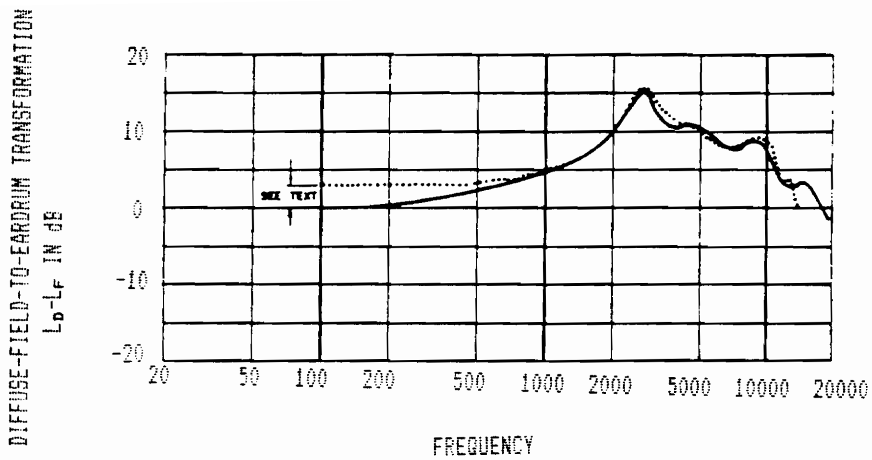


Figure 5. Average of five sound pressure measurements from a diffuse field to the eardrum taken on a KEMAR manikin. Dotted line does not pertain to this paper (adapted from Killion, 1979).(modified by the author).

to determine the values on these curves, direct measurements and indirect measurements. Direct measurements were recorded by placing a microphone against the eardrum to measure the SPL incident directly upon the eardrum. Indirect measurements were recorded by placing a microphone at the ear canal opening to measure the SPL at that location. A transfer function was then developed and applied to the indirect measurements to equate them with the direct measurements. Details of this transfer function were described by Shaw (1974).

One family of curves shows the difference between the reference SPL at the eardrum for a 0° angle of incidence and the SPL at the eardrum for another angle of incidence as a function of frequency. The reference SPL at the eardrum was obtained for each frequency (υ) at the 0° angle of incidence. This value was labeled $L_d(0,\upsilon)$. Then the angle of incidence (θ) and the frequency (υ) of the source were varied. The SPL at the eardrum for each of these conditions was measured and labeled $L_d(\theta,\upsilon)$. Each reference SPL (for each frequency) was subtracted from its corresponding SPL (for each frequency) of the new angle and labeled $D_d(\theta,\upsilon)$. Specifically, $D_d(\theta,\upsilon) = L_d(\theta,\upsilon) - L_d(0,\upsilon)$. Figure 6 shows the geometry of these measurements. $D_d(\theta,\upsilon)$, the azimuth

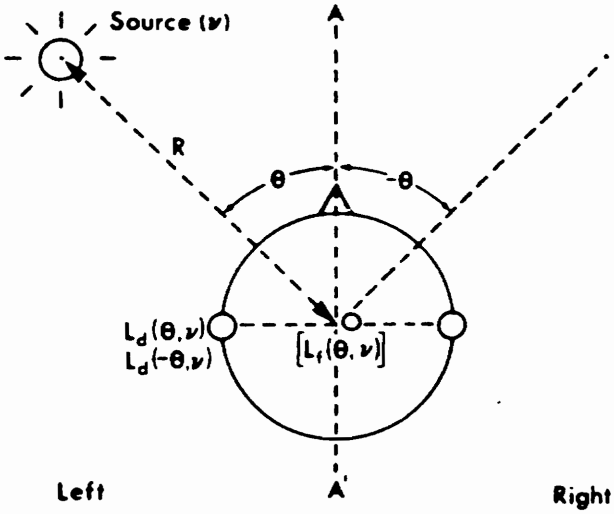


Figure 6. Geometry of measurements taken by Shaw (1974) (adapted from Shaw, 1974).

dependence function, is plotted in Figure 7 for various frequencies (Shaw, 1974).

According to Figure 7, top and middle panels, as the source moves from 0° to 90°, the SPL at the eardrum increases at almost all frequencies. However, beginning at approximately 60° the SPL level around the 4000 Hz band begins to decrease, falling below the reference SPL at 90° and continuing this trend through 180° (lower panel), while gradually widening to include the frequencies around it. The effect on the opposite ear is represented by the negative angle curves (Shaw, 1974). These curves show that the SPL at the eardrum is different for different angles of incidence and/or different frequencies. Thus, in a sound field which is less than diffuse, one may hear better or worse than in a diffuse field of equal SPL, depending upon the angle of incidence of the majority of the sound energy and the frequency of the sound source.

The second family of curves (Figure 8) shows the difference between the SPL at the eardrum and the SPL at the head center position as a function of direction and frequency. The SPL at the head center position was measured without the subject present at different angles of incidence (θ) and frequencies (υ), and labeled $L_f(\theta,\upsilon)$. The subject was then seated in the chamber and the angle of incidence

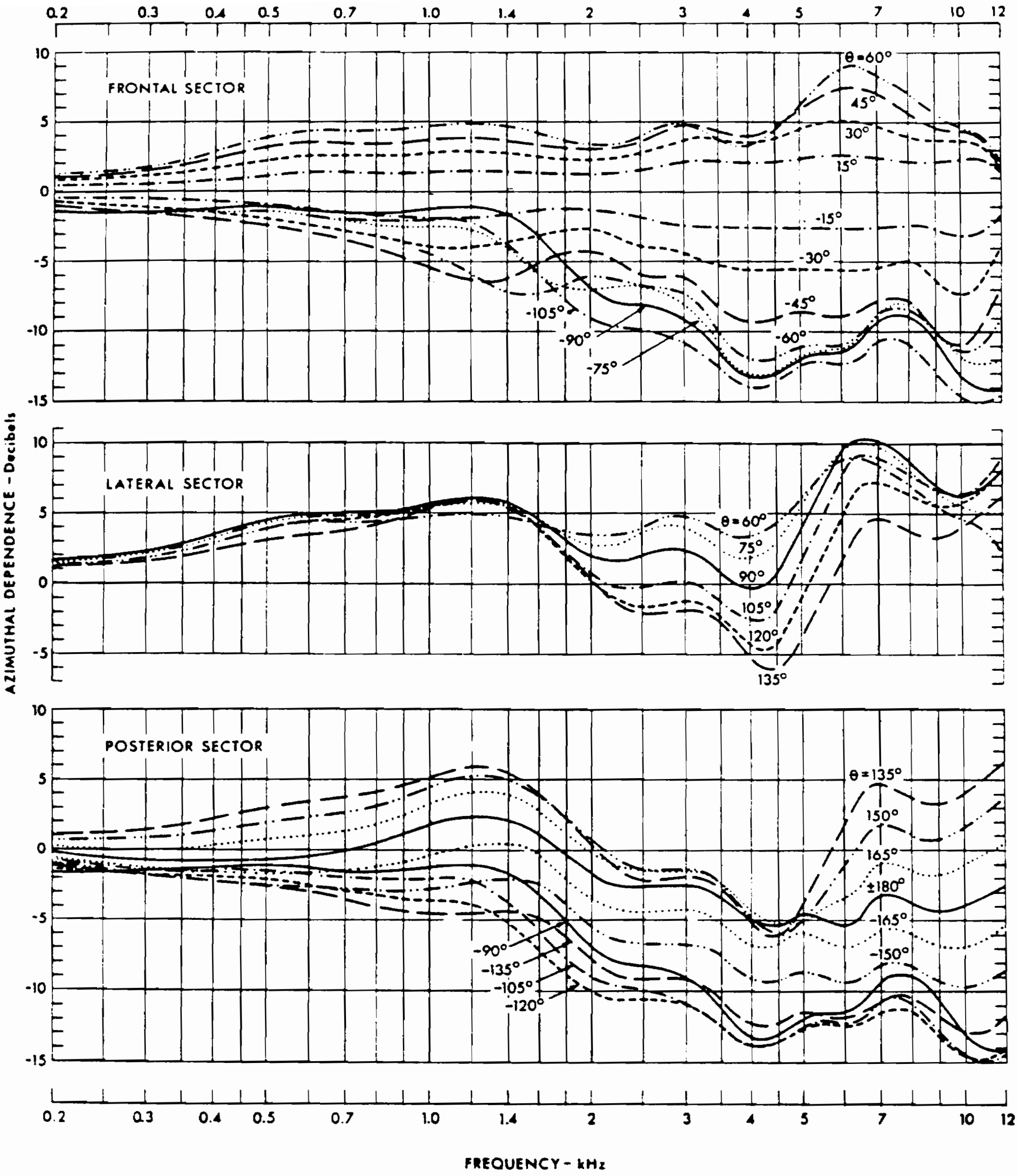


Figure 7. Family of curves showing the difference in sound pressure level in 15° intervals at the eardrum as a function of direction and frequency, with 0° as the reference location. Family is divided into three panels to minimize overlapping (adapted from Shaw, 1974).

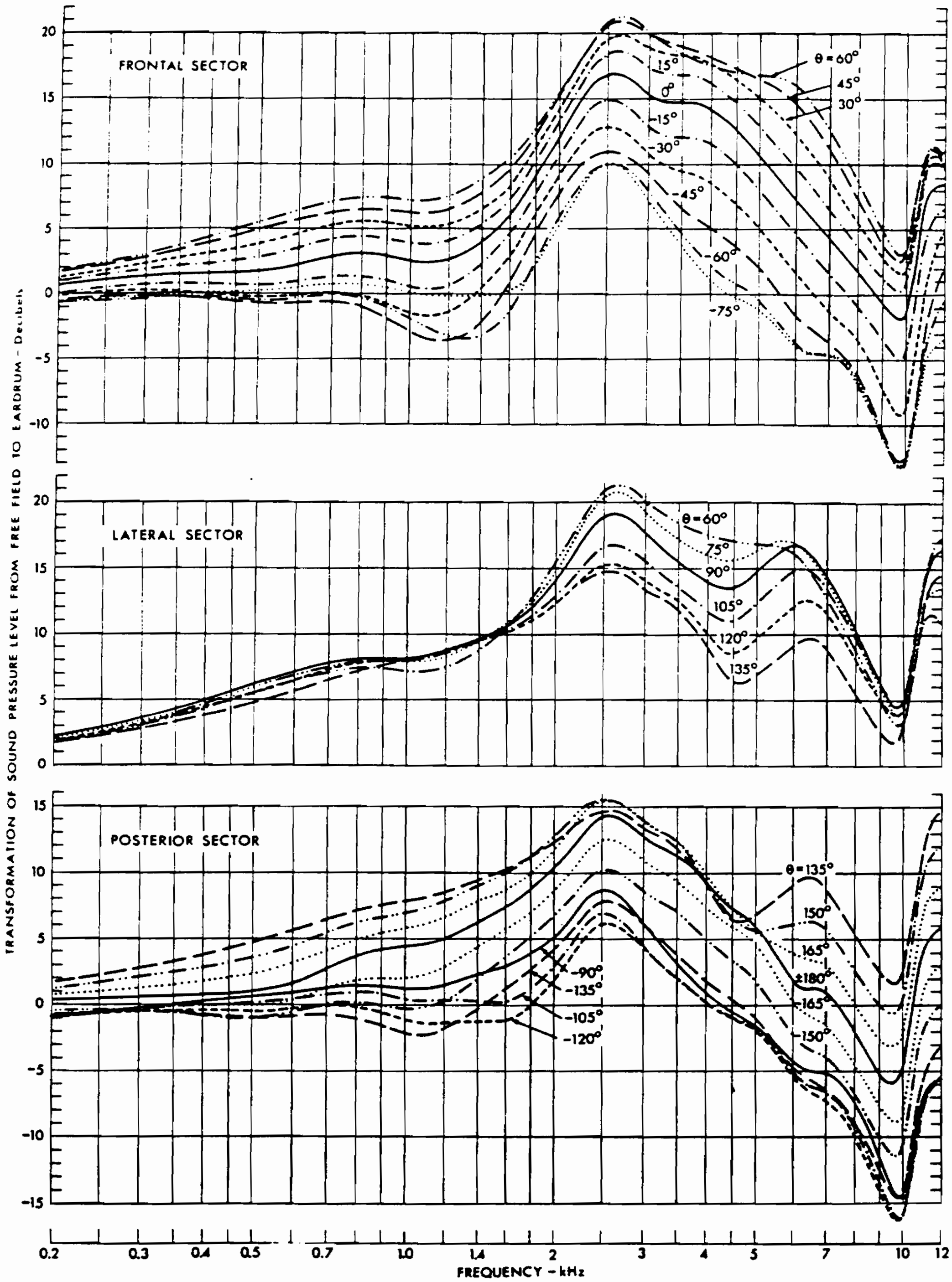


Figure 8. Family of curves showing the difference between the sound pressure level at the eardrum and the sound pressure level at the head center position as a function of direction and frequency, in 15° intervals. Family is divided into three panels to minimize overlapping (adapted from Shaw, 1974).

and the frequency of the source were again varied. The SPL at the eardrum for each of these conditions was measured and labeled $L_d(\theta,\nu)$. Each head center position SPL was then subtracted from its corresponding SPL at the eardrum and labeled $T_d(\theta,\nu)$. Specifically, $T_d(\theta,\nu) = L_d(\theta,\nu) - L_f(\theta,\nu)$. $T_d(\theta,\nu)$ represents the sound pressure level transformation from the free field to the eardrum and is plotted in Figure 8 for varying frequencies (Shaw, 1974).

Figure 8 shows a large increase in SPL at almost all frequencies as the angle increases from 0° to 60° (top panel). At approximately 60°, the trend tends to decrease, especially in the frequencies above 2000 Hz, although the SPL there is still greater than at the head center position. The largest increase in SPL occurs at about 60° and 2500 Hz. The effect on the opposite ear is represented by the negative angle curves (Shaw, 1974). This graph shows how the head and outer ear modify the sound in the free field, without the subject present, in response to varying frequencies and angles of incidence when exposed to a directional sound field. It shows which frequencies are attenuated and which are amplified and its dependence on angle of incidence and frequency.

Directionality Effects on the Occluded Ear

Very few studies have shown the effects of directionality on the occluded ear. Most of the studies that have examined these effects concentrated on the difference between the ANSI Z24.22-1957 standard and the ANSI S3.19-1974 standard, or the difference between the ANSI Z24.22-1957 standard and the British Standard BSI 5108:1974 (since updated to BSI 5108:1983).

The BSI 5108:1974 is similar to the ANSI S3.19 standard. It also specifies one-third octave bands of noise test signals centered around the same frequencies as S3.19 and presented in a diffuse sound field. However, the BSI 5108:1974 standard requires the diffuse sound field be generated in an anechoic chamber (free-field) through the use of four loudspeakers, instead of a reverberant chamber through the use of three loudspeakers. In addition, the BSI 5108:1974 standard requires the use of 15 subjects, two replications each, while the S3.19 standard uses 10 subjects, three replications each (Whittle and Robinson, 1977).

Therefore, these studies compared the difference that a highly directional sound field with pure tones and a diffuse sound field with one-third octave noise bands have on REAT values. As a result, the effects of the sound field directionality were confounded with the signal characteristics.

It has been shown, however, that for attenuation, pure tones and one-third octave noise bands are not significantly different. In Waugh's study, the largest difference (approximately 3 dB, with pure tone resulting in higher attenuation) appeared at 4000 Hz, although this was not statistically significant (no significance level was reported) (Waugh, 1974). These conclusions generally agree with those made by Webster, Thompson, and Beitscher (1956). They compared pure tones with noise bands for an earmuff, an earplug, and a combination of the two, after applying a critical-band correction, and found that at only 1000 and 4000 Hz was there a significant ($p \leq 0.01$) difference among the conditions.

Bolka (1972) studied the effect of sound field directionality and signal characteristics on the attenuation of earmuffs and earplugs. He tested four earplugs and five earmuffs under five conditions (Table 1). The conditions that used a free-field sound environment and a single angle of incidence were conducted in an anechoic chamber with one loudspeaker. The diffuse field condition was performed in a reverberant room with three loudspeakers. He found that

TABLE 1

Test Conditions (A-E) for Study (Bolka, 1972)

Condition	Stimulus	Sound Field	Angle of Incidence
A	Pure tone	Free	Frontal (0°)
B	One-third octave band noises	Free	Frontal (0°)
C	One-third octave band noises	Diffuse	--
D	Pure tone	Free	Side (90°)
E	One-third octave band noises	Free	Side (90°)

neither the sound field nor the signal characteristics resulted in a significant difference in attenuation for earplugs. However, the sound field characteristics resulted in a significant difference for earmuffs (at 1000, 2000, 3000, and 4000 Hz), with the data measured in the directional field yielding significantly higher attenuation than that obtained in the uniform field, although these results are confounded with signal characteristics (Figure 9). To interpret these results, Bolka suggested that they are probably partly due to diffraction, with the air leaks sometimes being shielded from the directional sound source. However, no statistical evaluations of the standard deviations of the attenuation values were reported for these two conditions.

Berger (1985a) reported similar results. He studied the difference in attenuation reported by the ANSI Z24.22-1957 standard and the ANSI S3.19-1974 standard for one earmuff and one earplug. The Z24.22 standard resulted in higher attenuation values than the S3.19 standard for the earmuff (Figure 10), but no difference was found for the earplugs (Figure 11). In both cases, though, the standard deviations were slightly lower for the S3.19 data (Berger, 1985a). No theories or explanations were suggested to

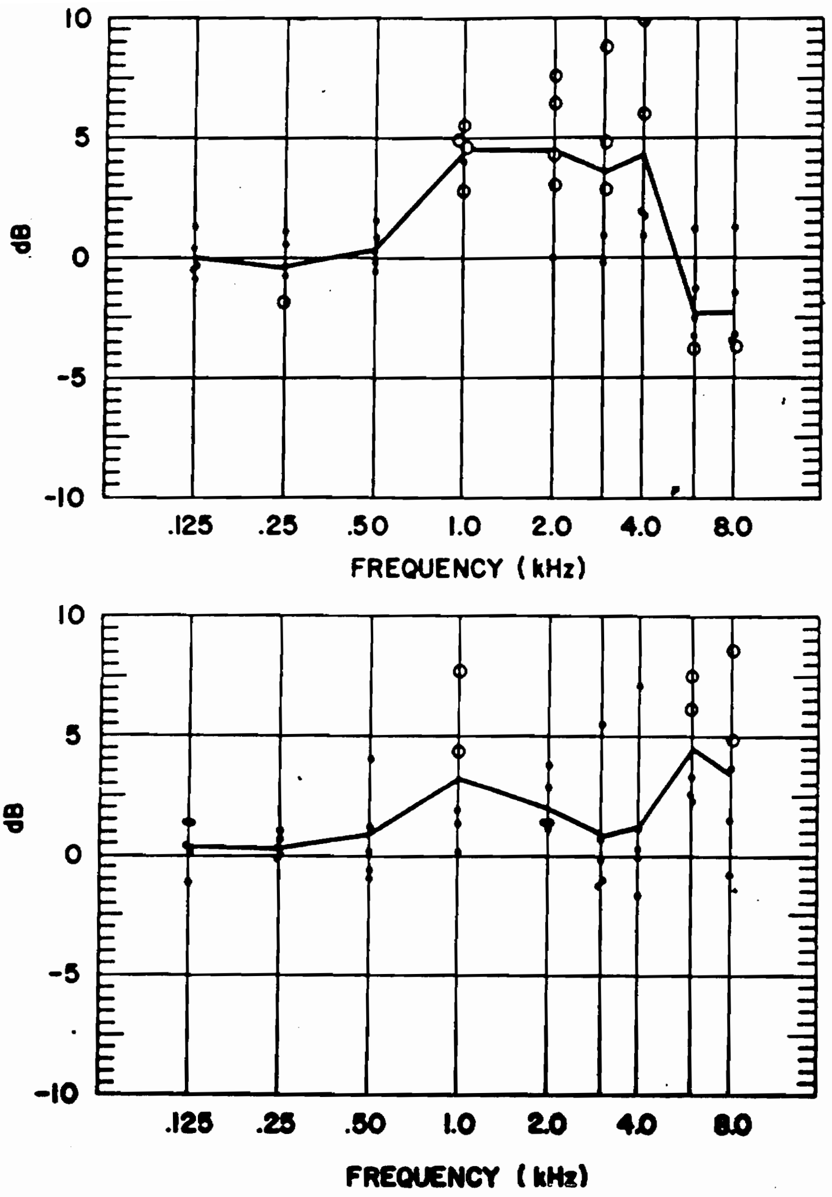


Figure 9. Top: Difference in attenuation values for earmuffs between a 90° highly directional source and a diffuse field. Bottom: Difference in attenuation values for earmuffs between a 0° highly directional source and a diffuse field. Open circles represent individual significant values, solid line represents mean values (adapted from Bolka, 1972; modified by the author).

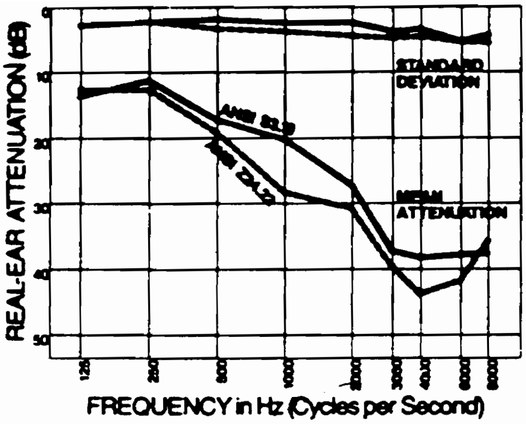


Figure 10. Earmuff attenuation measured under ANSI Z24.22-1957 and ANSI S3.19-1974 (adapted from Berger, 1979).

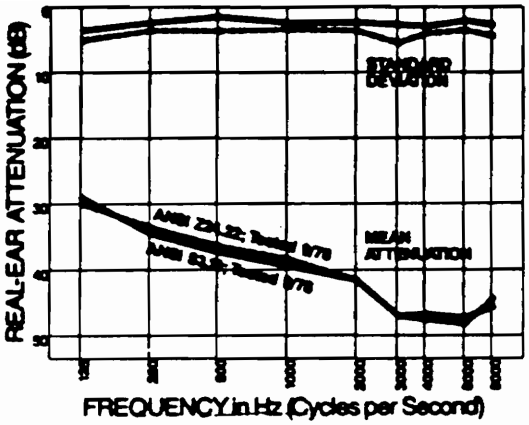


Figure 11. E-A-R slow-recovery foam earplug attenuation measured under ANSI Z24.22-1957 and ANSI S3.19-1974 (adapted from Berger, 1979).

interpret these results nor were data subjected to statistical analyses.

Martin (1977) studied the difference in HPD attenuation achieved under the Z24.22 standard and the BSI 5108:1974 standard. He tested nine HPDs, four sets of earplugs, and five earmuffs under both standards. He found no significant difference in attenuation between the two standards. However, through the use of the nonparametric Sign Test, he found a significant difference ($p < 0.05$) in standard deviations, with BSI 5108:1974 yielding smaller values.

Whittle and Robinson (1977) also studied the difference between the Z24.22 and the BSI 5108:1974 standards. They tested one earmuff and one type of earplug and found no significant differences for the earplugs in either attenuation mean or standard deviation, although they reported that the standard deviation tends to be lower under the BSI 5108:1974 standard. However, for the earmuff, the difference in attenuation obtained under the ANSI standard was found to be significantly lower at 1000 Hz ($p < 0.001$) and 3150 Hz ($p < 0.01$), and higher at 8000 Hz ($p < 0.001$). Again, a trend toward lower standard deviations was reported for the BSI 5108:1974 standard, but not enough to be statistically significant. Unfortunately, in neither case was the statistical test used to determine significance of the standard deviations specified. To explain some of these results, it was suggested that the sound diffraction effects occurring with pure tones but less so with 1/3 octave band stimuli, are responsible for the difference at 1000 Hz.

Bolka (1972) demonstrated the effect that the angle of incidence has on the attenuation of earmuffs. Using an anechoic chamber and a single loudspeaker, he rotated a manikin with a microphone at the ear canal opening in 30° increments to obtain a physical measure of attenuation. It can be seen in Figure 12 that the attenuation for a sample earmuff can vary by as much as 15 dB or 20 dB between 0° (incident frontally on the manikin face) and 90° (incident perpendicular to the manikin ear) angles.

Most of these studies show that the characteristics of the sound field can affect the attenuation estimates for HPDs, especially earmuffs. Therefore, the question becomes which sound field is the correct one. It would seem that the use of a diffuse field would be a more conservative choice for two reasons. One, prior data have shown that the diffuse condition results in lower attenuation values for earmuffs. Two, since it has also been shown that the angle of incidence can reduce the attenuation by as much as 15 to 20 dB and since the angle at which the sound in the actual situation will be incident upon the protector is unknown, it

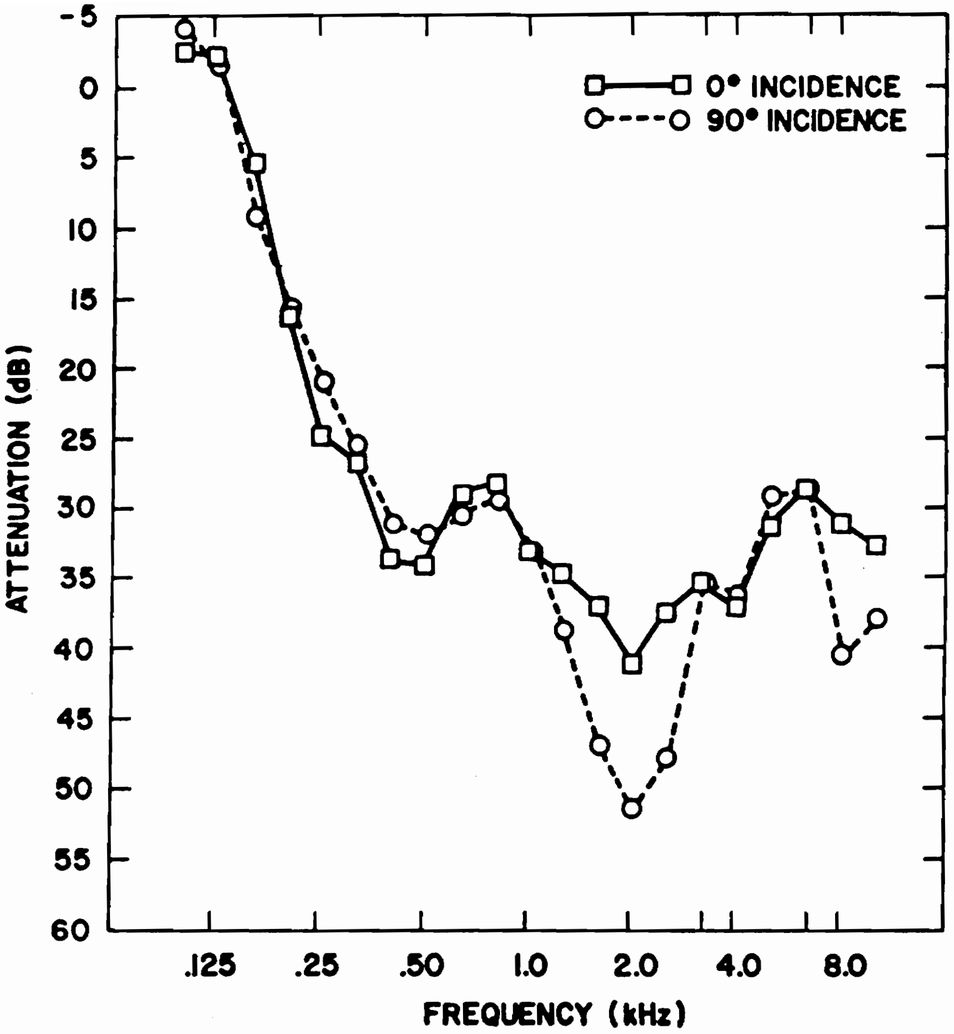


Figure 12. Sample earmuff attenuation measurements taken on a manikin for 0° and 90° incidence (adapted from Bolka, 1972).

may be better to specify a nondirectional sound field. Therefore, intuitively, it would seem a diffuse sound field is the better choice of the two conditions tested to date. Following this logic, any proposed change in the sound field should not result in significantly different attenuation estimates from those measured in the diffuse field.

However, these studies compared only the two extremes of sound field characteristics, the highly directional sound field (using a single loudspeaker in an anechoic field) and the diffuse sound field (using at least three loudspeakers in a reverberant field). None of these studies tested the effects of a moderately directional sound field. A moderately directional sound field is more easily achieved in practice in standard audiometric rooms than either an anechoic or reverberant environment.

Effect on Minimum Audible Field

The minimum audible field (MAF) is defined as the sound pressure level at the threshold of hearing in a free field with a frontally incident point source. It is crucial as a reference when performing many physiological/psychological experiments. Its use in HPD evaluations is often to determine the maximum amount of ambient noise allowed in a test chamber, for the ambient noise must be less than the threshold of hearing (Berger, 1981). One MAF value has been determined for each pure-tone octave band center ranging from 125 Hz to 8000 Hz, and an international standard has been adopted establishing these values (ISO, 1961). An MAF curve has been fit to these points, allowing intermediate MAF values to be approximated. However, the above MAF curve applies only to a highly directional free-field environment. With the current standard specifying a diffuse field, a new MAF curve is needed.

Robinson, Whittle, and Bowsher (1961) estimated a new MAF curve using a subjective technique. They compared the loudness of diffuse sound fields with the loudness of directional sound fields. Loudness in phons, a psychophysical metric, is based on human perception instead of physical measurement. Robinson et al. (1961) used pure tones for the directional field and narrow bands for the diffuse field. Subjects compared the loudness of a diffuse field with the loudness of a directional field to determine the point at which the two were equally loud. The difference in sound pressure level between the two equally loud sources was then recorded. This procedure was conducted four times with different sample sizes. The second, third, and fourth trials tested only selected frequencies from those used in the first trial. The results can be seen in Table 2 (Robinson et al., 1961).

These values were then compared with values obtained in two other studies, and a curve was fit to the data. This curve represents the difference between the two sound-field conditions and is, in the view of Robinson et al., the best estimate of this relationship (Figure 13). Figure 14 uses these data and adapts the 40-phon, equal-loudness contour and the MAF contour, both taken in a directional sound field, to present new curves that apply to a diffuse sound field (Robinson et al., 1961).

Berger (1981) used a different approach in that he determined a correction factor for estimating the MAF for a diffuse field from MAF data taken in a directional field. By averaging subjective and objective estimations of this relationship, a reliable correction factor was said to be achieved. The subjective estimation used was provided by an international standard, ISO 454-1975, in which the loudness of diffuse and free sound fields were compared (ISO, 1975). The objective estimation required the use of three existing studies. The data from Killion (1979) and Kuhn (1979) were averaged and used to determine the eardrum-to-diffuse-field amplification ratio (P_D/P_{DIF} where P_D is the eardrum pressure and P_{DIF} is the diffuse field pressure). The data from Shaw

TABLE 2

Loudness Comparison of Diffuse and Directional Fields. Values in parentheses are standard deviations (Robinson et al., 1961).

Team A - 26 observers
Team B - 24 observers
Team C - 27 observers drawn from A and B
Team D - 9 observers drawn from C

Mid-band frequency of test signal (KHz)	Difference between sound pressure levels (dB) in unobstructed plane wave in free field and in diffuse field, respectively, at equal loudness. The values are the average for the group shown.				
	Team A (dB)		Team B (dB)	Team C (dB)	Team D (dB)
1	1.5(2.1)				
1.25	1.5(1.6)				
1.6	2.9(3.2)				
2	2.1(2.5)			1.2	2.9
2.5	4.1(2.7)	2.9(3.2)	0.8	1.5	2.5
3.2	0.4(2.5)		-1.3	-1.0	-0.7
4	-1.5(2.4)	-1.1(2.7)		-2.2	-1.8
5		1.0(2.5)			
6.4		4.4(2.7)			
8		3.2(3.2)			
10		1.3(2.3)			

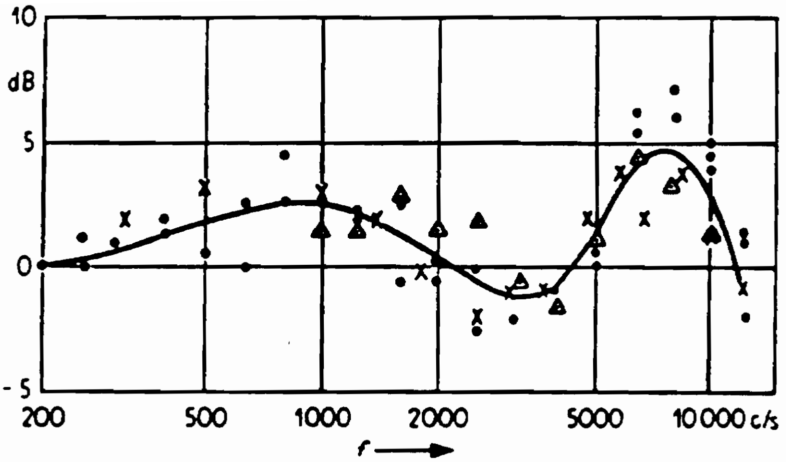


Figure 13. Directional versus diffuse field loudness comparisons. Positive values represent directional being louder. Solid line represents average of three studies with symbols differentiating the data from those studies (adapted from Robinson et al., 1961).

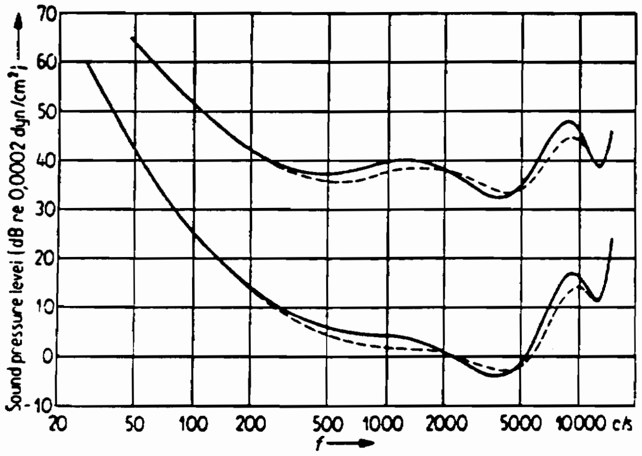


Figure 14. Equal loudness contours. Upper lines represent 40-phon contour. Lower lines represent MAF contour. Solid lines represent data taken with pure-tones presented at 0° incidence under free field conditions. Dotted lines represent solid-line data converted to data taken with narrow bands in a diffuse field (adapted from Robinson et al., 1961).

(1974) were used to determine the amplification ratio of the eardrum to free field (P_D/P_{FF} where P_D is the eardrum pressure and P_{FF} is the free-field pressure). By subtracting the eardrum-to-free-field amplification ratio from the eardrum-to-diffuse-field amplification ratio, the amount by which the diffuse field exceeds the free field can be determined, when the sound pressure level at head center position (with the subject or manikin removed) is the same for both cases ($P_{DIF}/P_{FF} = P_D/P_{DIF} - P_D/P_{FF}$). This amount is the objective estimation of the correction factor and, when averaged with the subjective estimation and added to a diffuse field threshold, can be used to find the MAF. Table 3 reproduces these correction values. These values represent the differences in the sound pressure levels at the threshold of hearing between a free field with a frontally incident point source and a random-incidence field.

Bolka (1972) was also concerned with converting data measured in one environment to data measured in another environment. Specifically, he wanted to convert data measured under ANSI Z24.22 to data measured in a diffuse, reverberant room with one-third octave noise test signals (condition C). To do so, he tested five earmuffs in the two environments and used the mean difference in attenuation

TABLE 3

Correction Values for Diffuse Field (Berger, 1981)

1/3 OB Center (Hz)	Correction Value
100	0
125	0
250	0
500	1.0
1000	2.5
2000	-2.0
2500	-2.5
3150	-2.5
4000	-2.0
6300	2.0
8000	5.0

between the two conditions as a correction factor. This procedure is tenuous because attenuation data are naturally very variable. Attenuation data depend not only on using a psychophysical procedure the results of which will vary between tests (even under the same conditions) to determine the occluded and the unoccluded thresholds, but they also depend upon the seal of the hearing protector, which adds variability to the procedure.

OTHER FACTORS AFFECTING HPD ATTENUATION

Gender

Casali, Lam, and Epps (1986) and Abel, Alberti, and Rokas (1988) studied the effects of gender on hearing protector attenuation. Casali et al. (1986) used the ANSI Z24.22-1957 procedure to test earplugs, canal caps, and earmuffs. They found that males achieved greater attenuation than females across the five earplugs, but that no there was no difference for the canal caps and earmuffs. Abel et al. (1988) confirmed these results when they tested four earplugs under supra-aural earphones which rested directly on the pinnae. However, the pressure of the earphones on the plugs, which could potentially cause plug conduction effects, may have compromised the results in this study. In any event, anatomical differences between the sizes and shapes of males' and females' ear canals comprise one possible explanation for the results of the above studies.

Hearing Level

Berger (1985b) examined the effects of hearing level (HL) on HPD attenuation. Hearing level, expressed in dBHL, is the level above or below "normal" hearing (as represented by the MAF curve for sound field measurement or Minimum Audible Pressure [MAP] curve for earphone measurement) that is required for a person to hear the signal. He found that for normal subjects (HL < 20 dBHL), the attenuation achieved for 6300 Hz and 8000 Hz varied inversely with hearing level. This relationship was not as pronounced for subjects with elevated hearing levels (HL > 20 dBHL) (Berger, 1985b).

Anatomy

The anatomy of the head, pinna, and ear canal can affect the attenuation achieved by the hearing protection device. As mentioned earlier, people with particularly large pinnae, prominent cheek bones, or other severe depressions may be difficult to fit properly with earmuffs and thus may affect the attenuation achieved. In addition, people with small ear canals or sharp bends in their ear canals may be difficult or impossible to fit with earplugs. Even people with average-sized ear canals may choose the wrong size earplug (if more than one size is available) and thus reduce the attenuation achieved. All these factors must be taken into consideration, especially when the HPD is being evaluated for the purpose of EPA-required labeled attenuation values.

Subjects

Berger, Royster, Casali, Merry, Mozo, and Royster (1990) suggested that experienced subjects may achieve higher attenuation values than novice subjects, on the basis of a pilot study performed for the development of a new REAT protocol for use in ANSI standards. However, this study used only two earplugs, so the effect on earmuffs and canal caps is unknown. In addition, because it was a pilot study, the sample size was quite small. A follow-on experiment is currently underway.

NOISE REDUCTION RATING (NRR)

Once the attenuation values have been obtained for a sample of subjects, these values must be arithmetically averaged to determine the mean attenuation that device provides at the individual frequencies (125, 250, 500, 1000, 2000, 4000, and 8000 Hz). However, given just these values, it is difficult to determine the overall attenuation provided by the device. It is not simply an average of the individual attenuation at each test frequency. Several methods are used to the determine overall attenuation, but the one required for product labeling purposes is the Noise Reduction Rating (NRR) (EPA, 1990).

The NRR is a single number, used to estimate the amount of protection afforded by an HPD and thus the noise exposure of the wearer. The EPA requires that this value be displayed on the packaging, along with the mean and standard deviation attenuation values at each test frequency (EPA, 1990). To determine the NRR of a device, the mean and standard deviation of the attenuation values at each individual frequency must be used in a series of calculations, a sample of which is provided in Table 4. To use the NRR to estimate the exposure of the wearer, an A- or C-weighted dB measure of the ambient noise is required. If

TABLE 4

Example of an NRR Calculation (Format from Berger, 1986b; Calculations from EPA, 1990)

	Octave Band Center Frequency (Hz)							
Spectral Values (dB)	125	250	500	1000	2000	4000	8000	dB(X)[1]
1. Assumed sound pressure levels	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
2. C-weighting correction	-0.2	0.0	0.0	0.0	-0.2	-0.8	-3.0	
3. C-weighted sound levels (step 1 - step 2)	99.8	100.0	100.0	100.0	99.8	99.2	97.0	107.9 (dBC)
4. A-weighting correction	-16.1	-8.6	-3.2	0.0	+1.2	+1.0	-1.1	
5. A-weighted sound levels (step 1 - step 4)	83.9	91.4	96.8	100.0	101.2	101.0	98.9	
6. Average attenuation at frequency	21.0	22.0	23.0	29.0	41.0	45.0[2]	38.5[3]	
7. Standard deviation x 2	7.4	6.6	7.6	9.4	6.6	6.7[2]	12.6[3]	
8. Estimated protected A-weighted sound levels (step 5 - step 6 + step 7)	70.3	76.0	81.4	80.4	66.8	62.7	73.0	85.1 (dBA)
9. NRR = step 3 - step 8 - 3[4] NRR = 107.9 - 85.1 - 3 = 19.8 dB[5]								

[1] Logarithmic sum of 7 octave band levels in the row.

[2] Arithmetic average of data taken at 3150 Hz and 4000 Hz

[3] Arithemetic average of data taken at 6300 Hz and 8000 Hz

[4] This is the 3 dB spectral uncertainty

[5] Round values less than and ending in 0.5 to the next lower whole number and values greater than 0.5 to the next higher whole number

a C-weighted measure is obtained, the NRR is simply subtracted from that value. If an A-weighted measure is obtained, the NRR must first be reduced by seven and then subtracted from that value. This reduction by seven is necessary because the accuracy of the NRR value is compromised when it is compared with a dBA measurement (Berger, 1986b).

One problem with the use of the NRR values is that they overestimate the performance of HPDs in the field. Many studies that demonstrate this effect have been conducted (e.g., Park and Casali, in press[a]). Therefore, it is recommended that the NRR be reduced. Berger (1983) suggested subtracting 10 dB from the value, and a note on the manufacturer's label required by the EPA suggests dividing the value by two before using it to estimate the exposure of the user.

RESEARCH OBJECTIVES

From the previous discussion, it can be concluded that the effect different levels of sound field directionality have on hearing protector attenuation has not been fully determined. The previous research in this area compares only the effects of the two extreme sound fields, a highly directional (anechoic, one frontally incident loudspeaker) and a diffuse (reverberant, three loudspeakers) sound field. Therefore, the purpose of this research was to:

(1) Determine if a completely reverberant, random-incidence field is necessary and establish whether reductions in diffusivity, as experimentally implemented by speaker placement and acoustic wall treatment modifications, should be allowed in ANSI testing standards.

(2) Determine if the effects of degrading the diffusivity of the sound field differs for different types of hearing protectors.

It was hypothesized that earplugs would not show a sound field main effect, since the conditions tested in this experiment were between the extreme conditions of sound field directionality tested in previous experiments which show no effect. However, the effect of the different sound fields on earmuff attenuation was not as readily predictable. It was speculated, however, that earmuff attenuation will tend to increase as the sound-field diffusivity degrades (i.e., the incidence becomes more directional), essentially providing midpoints for the trend established in previous studies of significantly different attenuation values between the extreme sound-field conditions. An interaction effect between sound field and hearing protector type was also anticipated due largely to the fact that the above trend is expected of the earmuffs but not of the earplugs.

EXPERIMENTAL FACILITY AND APPARATUS

The experimental facility used is located within the Auditory Systems Laboratory at Virginia Tech. It includes a reverberant chamber calibrated for REAT testing as per ANSI S3.19-1974, an integrated HPD test signal presentation and measurement system controlled by an IBM PS/2 Model 70 computer with printer (described later), a Beltone Clinical 114 pure-tone audiometer, and a Larson-Davis 3100 real-time spectrum analyzer with several laboratory-grade microphones for measurement and calibration purposes.

Reverberant Chamber

A modified Industrial Acoustics Corporation (IAC) audiometric booth was used. It is constructed of sheet steel double walls, separated by approximately 10 cm of fiberglass acoustic insulation. Affixed to the original walls and ceiling are an inner sheet of 1.27 cm thick gypsum board and an outer sheet of 0.64 cm thick hard-tempered masonite to establish a highly reflective surface. In addition, the carpet on the floor has been removed, exposing the bare sheet metal. The result of these modifications is a reverberant environment (measured reverberation times

[T_{60}] are given in Table 5) that meets the ANSI specifications of a reverberation time between 0.5 and 1.6 s for each 1/3 octave band test frequency (termed frequency) and all other ANSI requirements (to be discussed in further detail later) (ANSI, 1974; Casali and Robinson, 1990). The ambient noise levels present in the chamber are given in Table 6, and the interior and exterior dimensions of this modified chamber are provided in Table 7.

Reverberation times for this room and other sound-field conditions were measured using the Larson-Davis (L-D) 3100 spectrum analyzer, the L-D 2540 microphone, and the L-D 900B preamplifier. The room was excited with an 80-dB pink noise and once all filters were responding, the noise was abruptly shut off. The analyzer remained running, using linear averaging with a time constant of 0.05 s, until the noise had completely decayed and decay curves of the sound pressure level over time were plotted for each frequency. Reverberation times, T_{60}, were estimated using the linear portion of the decay curve to find the slope in s/dB, which was then multiplied by 60 dB.

The diffuse sound field requirements are met using three two-way loudspeakers, each oriented such that each loudspeaker's immission axis is directed toward a different room plane and not straight toward the subject. One

TABLE 5

Test Chamber Reverberation Times

1/3 Octave Band Center (Hz)	Reverberation Time, T_{60} (s)
125	0.56
250	0.89
500	1.49
1000	1.36
2000	1.27
3150	1.14
4000	0.99
6300	0.85
8000	0.80

TABLE 6

Test Chamber Ambient Noise Levels (Adapted from Casali and Robinson, 1990)

Octave Band Center (Hz)	Permissible Ambient Noise Levels (dB)[1]	Measured Ambient Noise Levels (dB)
125	24	20
250	18	14
500	16	6.5
1000	16	4.5
2000	14	2.7
3150	--	--
4000	9	5.1
6300	--	--
8000	30	8.1

[1] As per Table 1, ANSI S3.19-1974.

TABLE 7

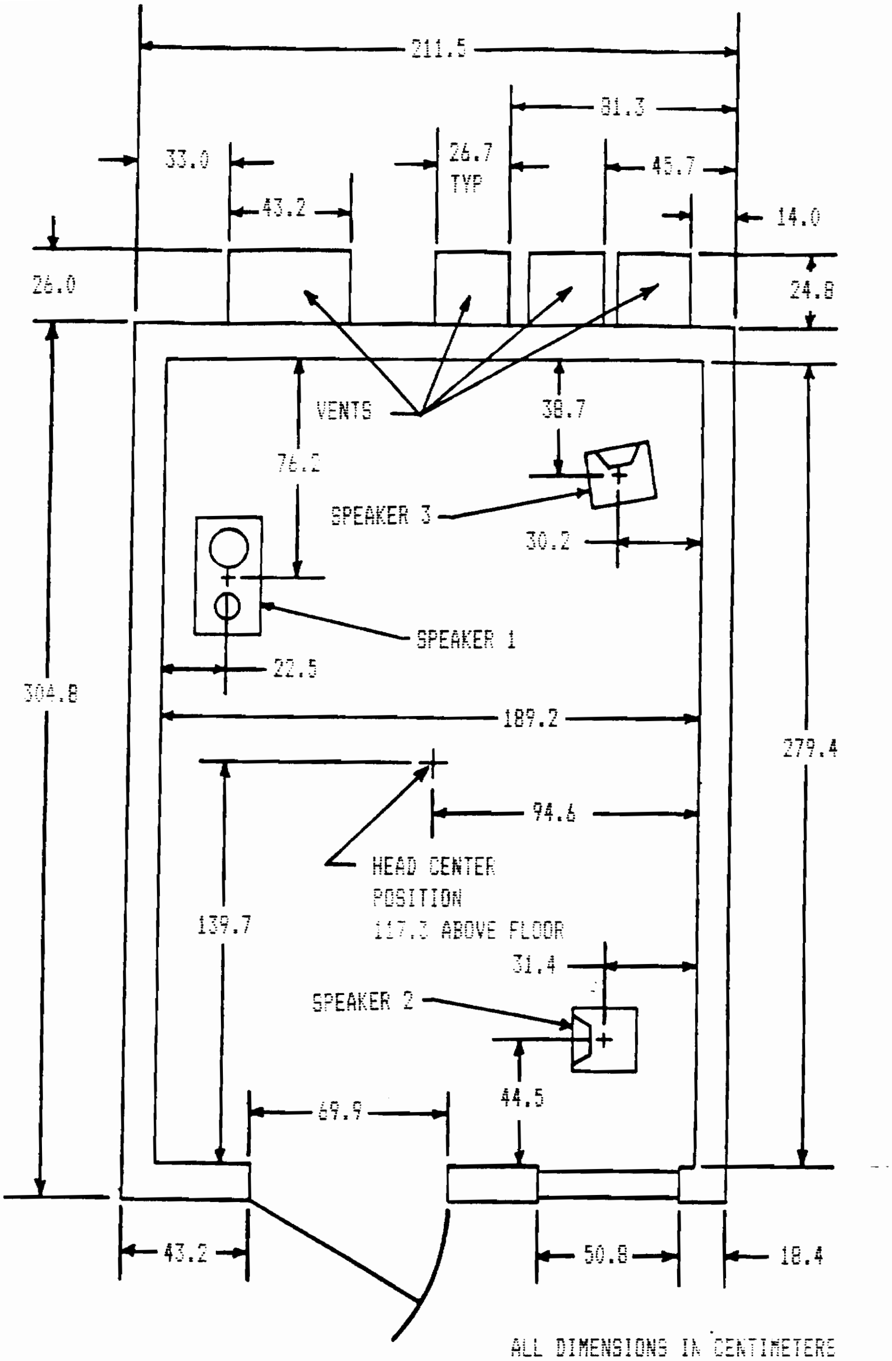
Interior and Exterior Dimensions of Reverberant Chamber (Adapted from Casali and Robinson, 1990)

	Interior Dimensions (cm)	Exterior Dimensions (cm)
Length	279.40	304.80
Width	188.60	211.46
Height	234.95	263.53

loudspeaker is oriented horizontally and directed toward the ceiling. Another loudspeaker is oriented parallel to the back wall and facing it, while the third is oriented parallel to a side wall, facing the opposite wall. The exact placement and dimensions are depicted in a schematic (Figure 15) and the room can be seen in a photo (Figure 16). This setup adheres to the ANSI S3.19-1974 standard sound field requirements (ANSI, 1974; Casali and Robinson, 1990).

HPD Test System

The system which was used to ascertain HPD attenuation in the experiment fully integrates the essential components necessary to generate the test signals and record the results. It includes an IBM PS/2 Model 70 microcomputer which controls the signal generation system and records the results, a Norwegian Electronics Type 828 system (noise generator, filter, amplifier, and attenuator networks) which generates the one-third octave band signals, three frequency-matched loudspeakers which present the signals in the sound field, and an Epson LX-800 dot-matrix printer which prints the results. The system uses three uncorrelated noise sources on three separate channels that produce test signals to be presented through three non-



ALL DIMENSIONS IN CENTIMETERS

Figure 15. Plan view of test chamber (adapted from Casali and Robinson, 1990, modified by author).

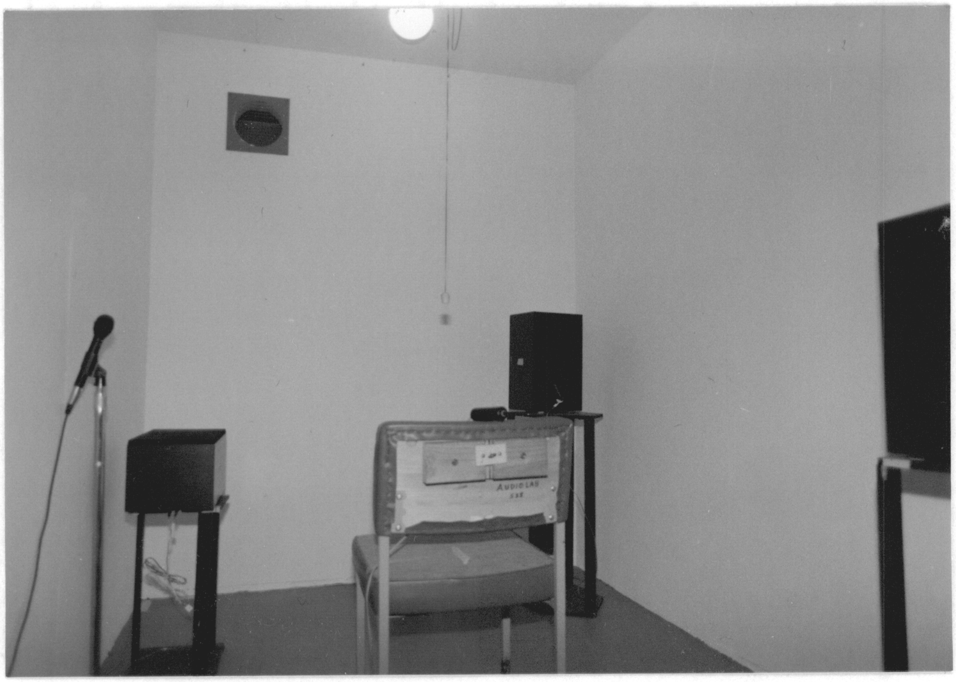


Figure 16. Photograph of test chamber.

coherent loudspeakers in the room. This setup helps avoid standing waves and other superposition effects. The signals presented were one-third octave band noises centered at 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz.

This system supports manual and automatic audiometric testing. The automatic mode, which incorporates the Békésy threshold tracking method, was used in this experiment (Békésy, 1947). To operate this system, the subject was seated in the chamber and given a quiet pushbutton to press. As soon as the subject heard the signal, he/she was required to press the pushbutton and hold it down until the signal was no longer heard, at which time he/she released the pushbutton. The system increased the signal level in the chamber at a rate of 5 dB/s while the pushbutton was not pressed and decreased the noise level in the chamber at the same rate while the pushbutton was pressed. This procedure was repeated for one test band until the criterion for a threshold determination was met, as described in ANSI S12.6-1984, at which time the test automatically moved to the next test band (criteria from S12.6 were used, since S3.19 specifies no such criteria; ANSI, 1984). The criterion for threshold determination that was used required at least four excursions (i.e., one excursion begins and ends with a pushbutton press or pushbutton release, termed a reversal) with no reversal valley greater than any reversal peak and no peak-to-valley difference less than 3 dB or greater than 20 dB (ANSI, 1984). The threshold level was the mean value of these excursions. All nine test bands were presented in this manner and a reliability check performed, repeating the procedure at 125 Hz after the ninth band.

Support instrumentation. In addition to the above HPD test system, support instrumentation was required. An intercom system was used to present instructions to the subject while in the test chamber. The experimenter was able to talk through headphones (when worn by the subject for audiometry) or through an additional loudspeaker located in the room, by operating a push-to-talk switch at the experimenter station. A "hot" microphone inside the chamber was used so that the subject need only speak to be in contact with the experimenter.

For screening the subjects, a Beltone Clinical Model 114 audiometer was used to present pure tones through a set of Telephonics TDH 50 earphones. The system was calibrated with an L-D Model AE100 artificial ear, an ACO Model 7023 one-inch (2.54 cm) microphone, and an L-D Model 800B precision sound level meter with a 1/3 octave filter set. Other measurement instrumentation used to calibrate the test system included an L-D 3100 real-time spectrum analyzer and one or more of the following microphones and/or preamplifiers: an L-D Model 2540 half-inch (1.27 cm) microphone, an ACO Model 7023 one-inch (2.54 cm) microphone, an L-D Model 900B preamplifier, and an L-D Model 825-10 preamplifier. A 1000-Hz, 94 dB(linear) standard sound source (Brüel and Kjær Model 4230) was used to calibrate the microphone/analyzer measurement system before each facility calibration was performed.

EXPERIMENTAL DESIGN

A four-way, complete factorial, mixed-factors experimental design was used for this experiment. Such a design allowed for the evaluation of all main effects and interactions. The full matrix is shown in Figure 17.

Independent Variables

Overview. The four variables manipulated in this experiment were the sound-field environment (E) used to test the hearing protectors, the hearing protector (H), frequency (F), and gender (G).

Sound-field environment. Sound field, a within-subjects variable, had three levels. The first level (hereafter, reverberant, three-speaker sound-field environment) used all three loudspeakers in the reverberant test chamber to provide a random-incidence field, as required by ANSI S3.19-1974 and CSA Z94.2-M1984 and allowed by ANSI S12.6-1984, BSI 5108:1983, ISO 4869-1:1990, and SS 882151. This level meets all the requirements of the ANSI S3.19-1974 HPD attenuation testing standard.

The ANSI standard S3.19-1974 specifies three requirements regarding the sound field characteristics of

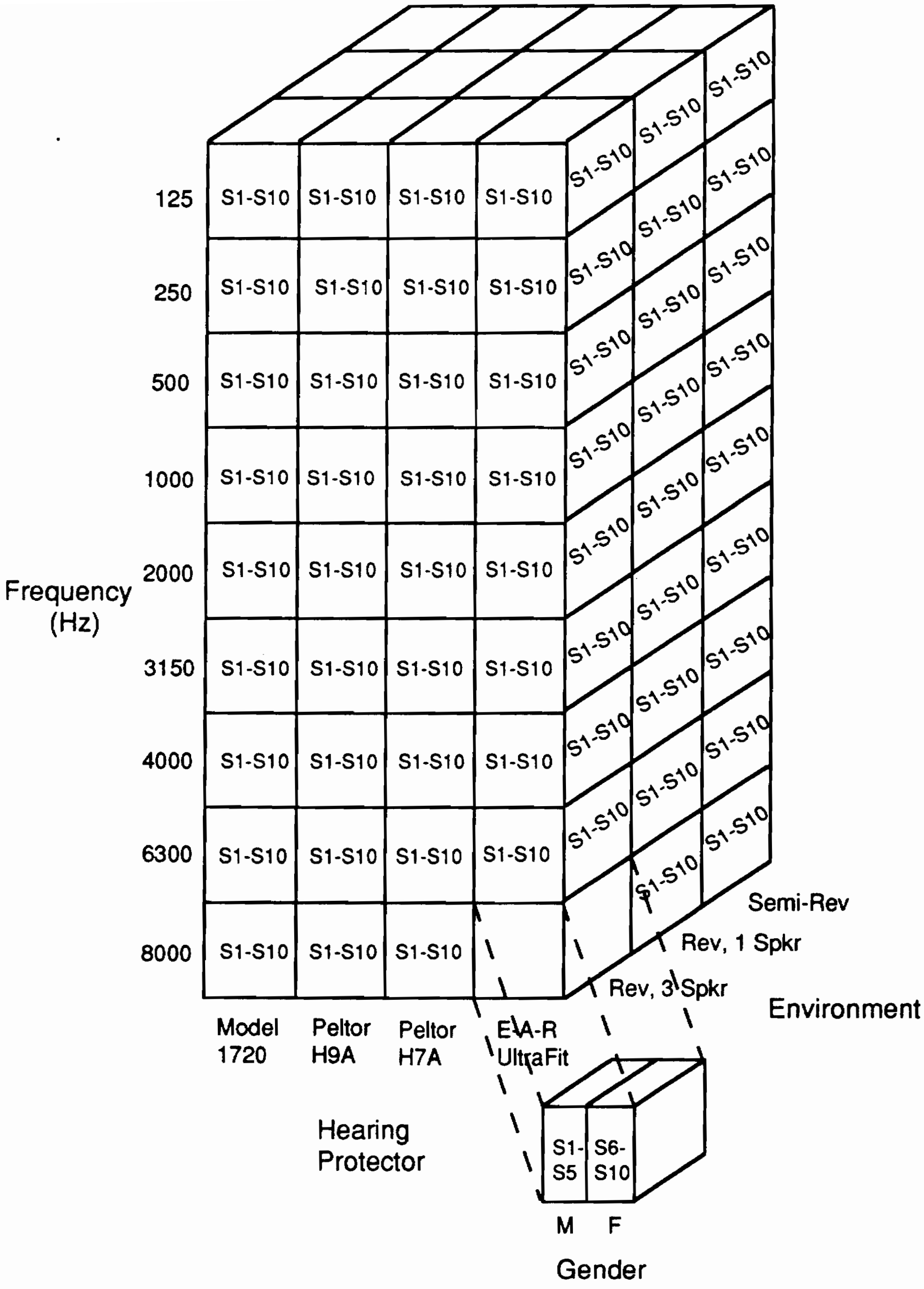


Figure 17. Experimental design matrix.

the test chamber. The first requirement is that the reverberation time (without the subject present) in the test space must be between 0.5 and 1.6 s for each of the test bands. Table 8 shows the reverberation time of the room for the first level of the environment variable. The decay curves used to compute the reverberation time for each level of the sound field variable can be found in Appendix B. The second requirement of the standard, uniformity, concerns the level of the sound field about the subject's head position. The standard requires that the difference in sound level measured at each of six positions about the subject's head center position be no greater than 6 dB, and that the difference in sound level measured right to left be no greater than 2 dB. The locations of these positions are shown in Figure 18 (ANSI, 1974). Table 9 shows the compliance of the room for the first level of the environment variable to the standard's six-position requirement.

The third requirement of the standard specifies that the sound field must have equal energy among the three planes. In one method of determining compliance, a figure-eight microphone must be placed at the subject's head position and rotated in 15-degree increments about each of the three perpendicular planes (X, Y, and Z). An average

TABLE 8

Reverberation Times for the Three Sound-field environments

1/3 OB c.f. (Hz)	Reverberation Time, T_{60} (s)	Reverberation Time, T_{60} (s)	Reverberation Time, T_{60} (s)
125	0.56	0.61	0.53
250	0.89	0.90	0.57
500	1.49	1.48	0.40[1]
1000	1.36	1.37	0.34[1]
2000	1.27	1.26	0.45[1]
3150	1.14	1.16	0.47[1]
4000	0.99	1.05	0.57
6300	0.85	0.90	0.43[1]
8000	0.80	0.79	0.43[1]

[1] T_{60} below the minimum specified by ANSI S3.19-1974.

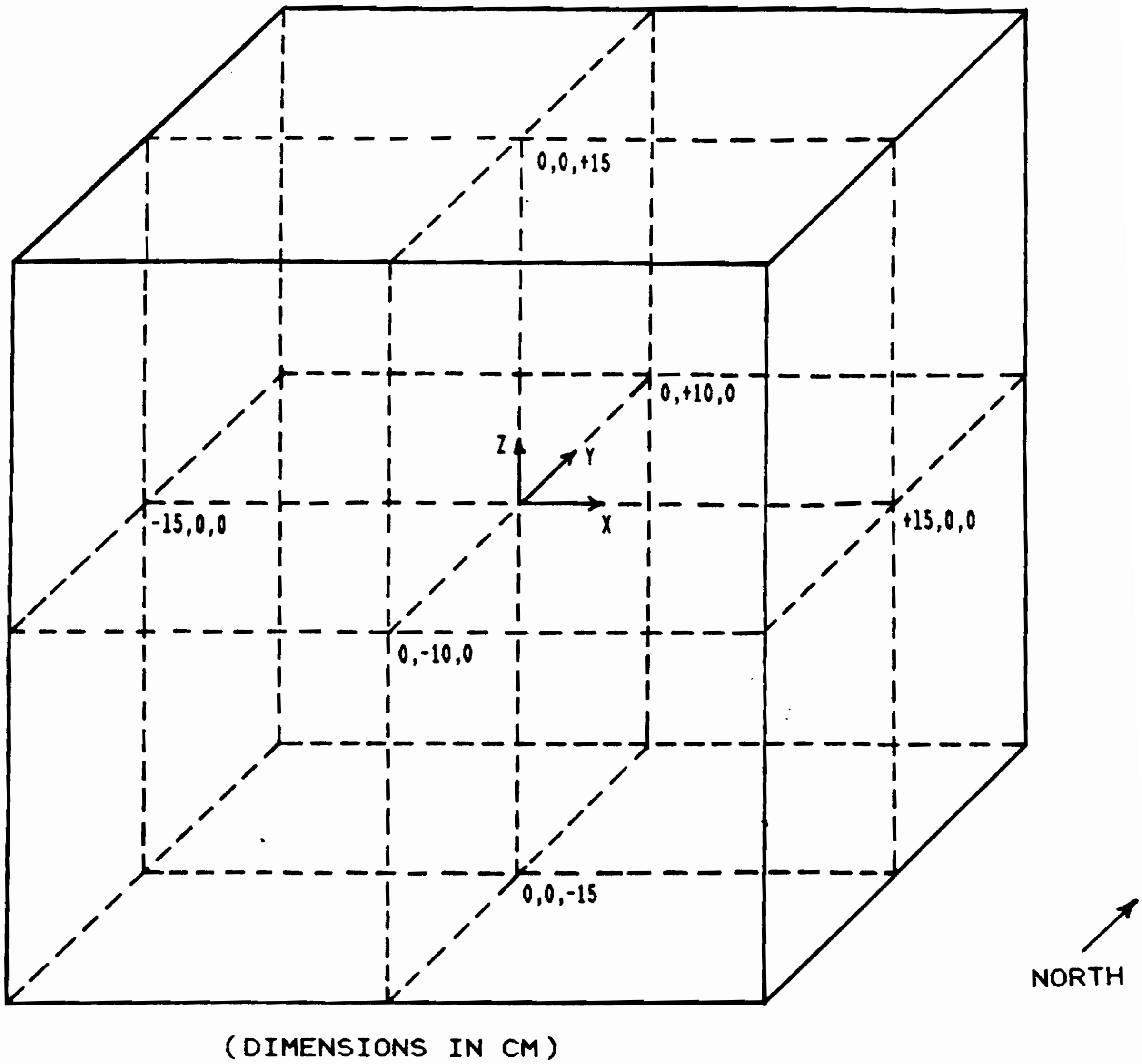


Figure 18. Microphone location of six position measurements relative to subject's head center position (adapted from Casali and Robinson, 1990).

TABLE 9

Test Signal Variation at Six Positions About Head Center for the Three Sound-field environments

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Reverberant, Three-Speaker Environment[1]

1/3 OB Center (Hz)	dB Right -15,0,0	dB Left 15,0,0	R-L D[2]	dB UP 0,0,15	dB Down 0,0,-15	dB Front 0,-10,0	dB Back 0,10,0	6-Pos D[3]
125	66.7	66.7	0.0	66.9	66.4	67.1	66.9	0.7
250	66.4	64.9	1.5	65.8	65.1	64.7	64.3	2.1
500	68.6	68.6	0.0	69.5	69.5	68.1	69.0	1.4
1000	67.9	68.2	0.3	68.4	68.8	68.3	67.9	0.9
2000	66.7	66.2	0.5	66.7	66.1	65.9	66.1	0.8
3150	63.0	63.0	0.0	63.2	63.7	62.9	63.8	0.9
4000	64.6	64.4	0.2	64.2	64.4	64.3	64.3	0.4
6300	61.8	61.8	0.0	61.7	61.9	61.9	61.5	0.4
8000	60.3	60.1	0.2	59.9	60.2	60.4	60.1	0.5

Reverberant, One-Speaker Environment

1/3 OB Center (Hz)	dB Right -15,0,0	dB Left 15,0,0	R-L D[2]	dB UP 0,0,15	dB Down 0,0,-15	dB Front 0,-10,0	dB Back 0,10,0	6-Pos D[3]
125	63.7	63.4	0.3	63.5	63.5	63.4	63.0	0.5
250	60.3	59.5	0.8	61.0	61.0	60.4	59.7	1.3
500	61.5	62.9	1.4	60.7	60.6	59.0	58.9	1.8
1000	60.2	60.4	0.2	61.3	61.2	61.9	62.0	0.8
2000	58.9	59.4	0.4	59.4	60.8	59.8	59.0	1.8
3150	56.1	57.5	1.4	57.2	56.9	56.8	57.2	0.4
4000	58.5	58.0	0.5	58.0	58.7	57.5	58.1	1.2
6300	53.9	54.9	1.0	55.3	54.9	54.7	55.0	0.6
8000	52.6	53.3	0.7	53.6	53.3	54.1	53.5	0.8

TABLE 9 -- CONTINUED

Semi-Reverberant Environment

1/3 OB Center (Hz)	dB Right -15,0,0	dB Left 15,0,0	R-L D[2]	dB UP 0,0,15	dB Down 0,0,-15	dB Front 0,-10,0	dB Back 0,10,0	6-Pos D[3]
125	60.5	60.5	0.0	60.6	59.4	61.0	59.6	1.6
250	65.3	64.9	0.4	66.0	64.8	65.0	64.9	1.2
500	62.2	63.8	1.6	66.0	67.0	64.9	64.5	4.8
1000	62.8	63.1	0.3	65.5	65.1	64.2	62.8	2.7
2000	61.1	61.1	0.0	61.7	62.0	62.8	63.5	2.4
3150	59.2	59.0	0.2	57.7	60.9	59.5	59.6	3.2
4000	58.8	58.6	0.2	59.9	60.5	59.6	60.3	1.9
6300	57.9	58.2	0.3	58.8	59.5	58.8	58.0	1.6
8000	57.6	58.1	0.5	57.4	57.9	58.9	57.7	1.5

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[1] Adapted from Casali and Robinson (1990).

[2] Absolute value dB difference between right and left microphone positions.

[3] Maximum absolute value dB difference between all pairs of the six microphone positions.

must then be computed for each plane and for each of the nine frequencies tested (125, 250, 500, 1000, 2000, 3150, 4000, 6300, 8000). The difference in the average sound levels among the three planes can be no greater than those shown in Table 10 for any of the nine test bands (ANSI, 1974). Appendix A shows the data for compliance of the first level of the environment variable to the standard's random sound field requirement and summary statistics are presented in Table 11. If a test chamber satisfies all three of these requirements, it is believed that a random-incidence (diffuse) field is obtained within that chamber.

The second and third levels of the environment variable progressively degraded the diffusivity of the room. The second level (hereafter, reverberant, one-speaker sound-field environment) was essentially the same as the first, except it used only one loudspeaker directed away from the subject instead of three loudspeakers. The loudspeaker used was directed toward the back wall, as described earlier. This condition still met all the requirements of the ANSI S3.19-1974 standard, except it used only one loudspeaker. The diffusivity was degraded from the first condition, but it still fell within the limits of the standard (Tables 8 and 9, and Appendix A). This condition was designed to simulate a test facility that could meet the requirements of

TABLE 10

Allowable Sound Field Variation (Adapted from Casali and Robinson, 1990)

1/3 OB c.f. (Hz)	Allowable Sound Field Variation (dB)[1]
125	4
250	4
500	4
1000	5
2000	5
3150	5
4000	4
6300	5
8000	5

[1] Using a dual diaphragm, directional microphone (AKG C414B-ULS) in its figure-eight pick-up pattern.

TABLE 11

Summary Statistics (Based on Appendix A) for Sound Field Directionality of the Three Sound-field environments (Data are in dB)

Reverberant, Three-Speaker Environment[1]

	1/3 OB Center (Hz)								
	125	250	500	1000	2000	3150	4000	6300	8000
Mean(X)	49.5	62.0	62.3	61.9	59.3	58.2	59.7	57.1	56.7
Mean(Y)	49.9	61.1	62.6	61.9	58.6	58.1	59.5	56.9	56.2
Mean(Z)	49.5	61.0	62.7	61.8	58.4	58.2	59.8	56.8	56.6
Δ Max	**0.4**	**1.0**	**0.4**	**0.1**	**0.9**	**0.1**	**0.3**	**0.3**	**0.5**

Reverberant, One-Speaker Environment

	1/3 OB Center (Hz)								
	125	250	500	1000	2000	3150	4000	6300	8000
Mean(X)	44.2	59.9	59.0	60.2	57.5	56.9	58.1	56.2	56.1
Mean(Y)	46.5	58.1	61.9	59.0	56.3	56.2	58.0	55.6	54.9
Mean(Z)	46.1	58.0	61.1	59.6	57.5	57.1	59.0	56.4	56.1
Δ Max	**2.3**	**1.9**	**2.9**	**1.2**	**1.2**	**0.9**	**1.0**	**0.8**	**1.2**

Semi-Reverberant Environment

	1/3 OB Center (Hz)								
	125	250	500	1000	2000	3150	4000	6300	8000
Mean(X)	41.0	58.8	62.2	60.2	57.3	56.5	57.3	56.8	56.6
Mean(Y)	37.7	53.1	58.5	56.0	51.7	52.6	54.8	53.1	52.7
Mean(Z)	39.4	55.5	59.3	57.1	55.9	54.9	56.0	56.9	56.8
Δ Max	**3.3**	**5.7**[2]	**3.7**	**4.2**	**5.6**[2]	**3.9**	**2.5**	**3.8**	**4.1**

---

[1] Adapted from Casali and Robinson (1990).

[2] Variation greater than that allowed by ANSI S3.19-1974.

the room and diffusivity, but was limited in equipment and had only one channel to drive a single loudspeaker.

The third level used one frontally incident loudspeaker and foam wall treatment (hereafter, semi-reverberant sound-field environment). One piece of 2-in. (5.08 cm) thick Sonex^{TM} acoustical foam was hung on each of the four walls, and together with the frontally incident loudspeaker, violated the standard's random-incidence criteria (Tables 8 and 9, and Appendix A). This test room is shown in the photograph in Figure 19. It was designed to simulate a test facility that had only a semi-reverberant room and a single-channel test presentation system. Note in Tables 8, 9, and 11 how the sound field is progressively degraded until it breaks the standard's criterion in the third level.

Hearing protection device. The hearing protector was a within-subjects variable with four levels. Two major categories of hearing protectors were used. Circumaural devices (earmuffs) and insert devices (earplugs) constituted the two categories because they comprise the majority of the HPDs used by the consumer. Also, because earmuff attenuation has been shown to change between the two extreme sound-field conditions and earplug attenuation has been shown not to change, three earmuffs which varied substantially in their design were selected. Only one

Figure 19. Photograph of the semi-reverberant environment.

earplug was tested to confirm the results of the previous studies. The three earmuffs included one (the Cabot Safety Model 1720) whose design made it difficult to fit on certain subjects (Figure 20), one small-volume earmuff (the Peltor H9A, Figure 21), and one large-volume earmuff (the Peltor H7A, Figure 22).

The two Peltor earmuffs were chosen because their most obvious design difference was earcup volume, and a comparison between these earmuffs would allow inferences to be made concerning volume and attenuation achieved in the various sound fields. The Model 1720 earmuff was chosen because if leaks in the protector were responsible for the earmuff attenuation differences between the extreme conditions found in previous studies, this earmuff was believed to be the most likely to show such differences. The earplug chosen for this study was the premolded, E-A-R UltraFit earplug (Figure 23).

Participants. Five males and five females of the Virginia Tech/Blacksburg community took part in the study as paid volunteer participants. Subjects ranged in age from 21 to 33 years old, with a mean of 26.1 years old. Experienced subjects were used exclusively. Novice subjects who participated were trained until they reached an acceptable experience level.

Figure 20. Cabot Safety Model 1720 earmuff.

Figure 21. Peltor H9A earmuff.

Figure 22. Peltor H7A earmuff.

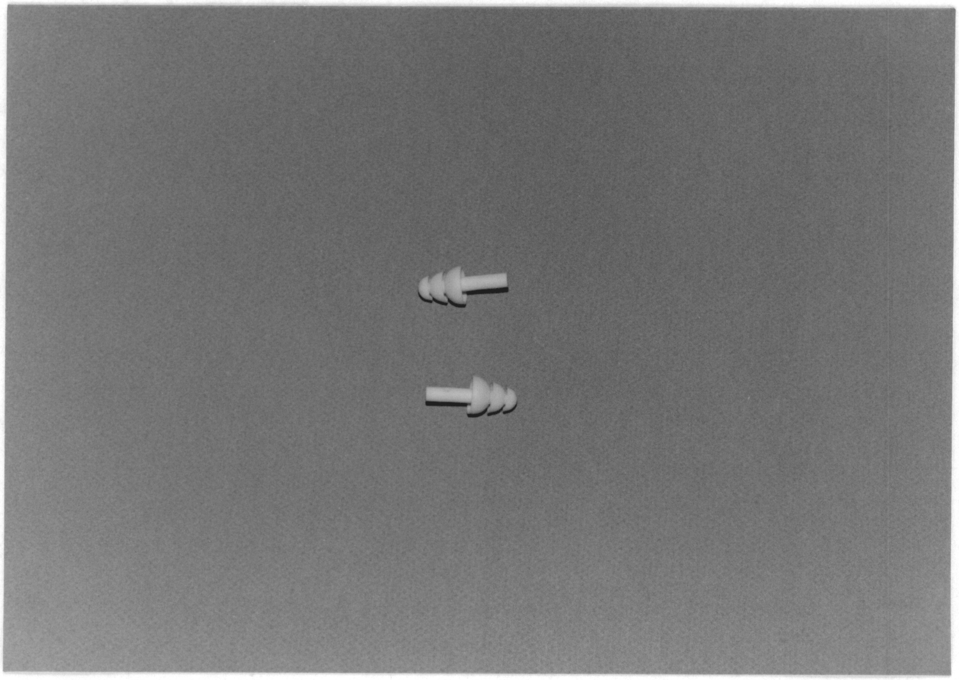


Figure 23. E-A-R UltraFit earplug.

For the purpose of this experiment, a person who had participated in at least one complete REAT test (three occluded and three unoccluded) within the previous year was considered experienced. To experience-level novice subjects, that person underwent a series of at least 6 to a maximum of 10 successive open thresholds in the test space, the last 3 of which could vary by no more than 6 dB at any frequency. If, after the 10th trial, the subject did not meet this criterion, that person was not able to participate in the experiment.

Prior to the experiment, each of the candidates was required to pass several screening tests. Each candidate was be asked to read a brief description of the experiment (Appendix C) and, if he/she fully understood the protocol and his/her rights as a subject, sign an informed consent form (Appendix D). All subjects were free from any otological disorders that may have adversely affected the outcome of the experiment, such as excessive ear wax. A brief otoscopic examination of the ear canal and tympanum was made using a Welch-Allen 21700 otoscope and each subject was asked if he/she suffered from any otological problems, such as ringing in the ears or tinnitus, excessive ear wax, intermittent hearing losses, etc., to ensure compliance. In addition, all candidates were required to have hearing threshold levels, in each ear, as measured by a pure-tone audiometer (Beltone Clinical Model 114), of less than 10 dB at the 125, 250, 500, and 1000 Hz test frequencies and less than 20 dB at 2000, 3000, 4000, 6000, and 8000 Hz test frequencies. The audiometry test was conducted in the sound-treated booth using Beltone TDH 50 earphones.

Each candidate was then required to pass a variability test, using the test signal presentation system, on three successive open-threshold trials using one-third octave bands with center frequencies of 250, 500, 1000, 2000, 3150, and 4000 Hz. The variability criterion states that no three successive threshold values obtained at one frequency can have a maximum range of 6 dB (ANSI, 1974). A maximum of 10 trials was allowed to meet this criterion. A subject who had been experienced-leveled did not need to undergo this test twice.

Other independent variables. Frequency was a within-subjects variable with nine levels, as required by the standard REAT test (125, 250, 500, 1000, 2000, 3150, 4000, 6300, 8000 Hz). Gender was a between-subjects variable with two levels, male and female. Thus, combining the within-subjects variables, excluding frequency because it did not require separate experimental sessions, each subject underwent 12 experimental sessions.

Treatment Condition Presentation

The presentation of all treatment conditions was completely randomized with a few restrictions. Half the subjects received the semi-reverberant sound field first, while the other half received either the reverberant, three-speaker sound field or the reverberant, one-speaker sound field first. These requirements were largely due to the fact that this study took place as part of a much larger study in which complete counterbalancing was infeasible.

Dependent Variable

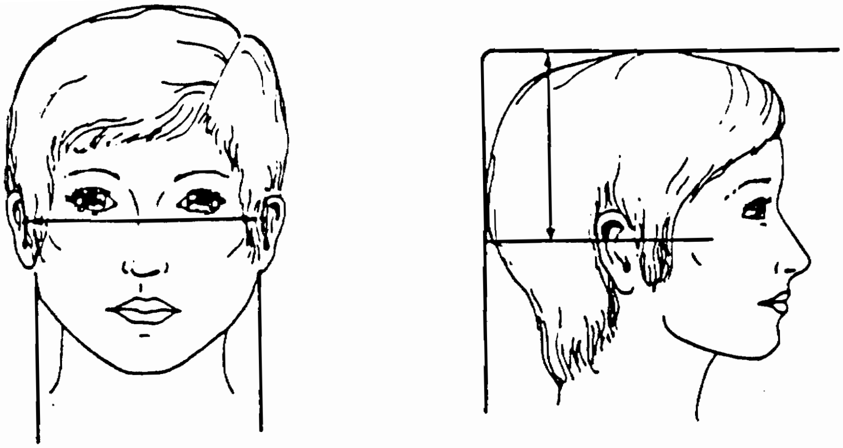
Attenuation in dB was the dependent variable. For each subject, three trial pairs (one unoccluded and one occluded test per pair) were obtained under each treatment condition for each of the nine test frequencies. For each trial pair at each frequency, the dB difference between the occluded and the unoccluded threshold constituted the attenuation for that trial. The attenuation scores were obtained in this manner using the REAT method specified by ANSI S3.19-1974 and other international standards for HPD attenuation testing.

Experimental Procedure

Screening and leveling procedure. The experiment required only one screening session, which served a dual purpose. One, it ensured that the subject met all the criteria for participation in the experiment, as described earlier, and two, it leveled the experience of the novice subjects, if necessary, so that all subjects in the subsequent experiment were equally experienced in threshold tracking.

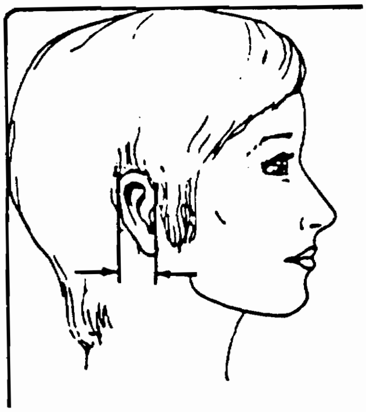
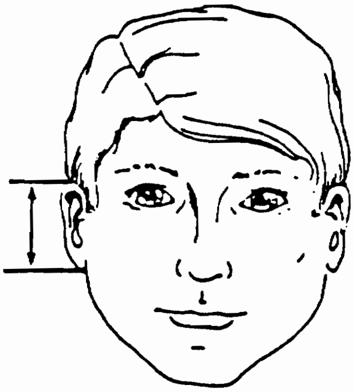
Upon arrival, the subject first read a description of the experiment and the informed consent form. After all questions were answered as fully as possible, the subject was asked if he/she wished to participate and, if so, to sign the informed consent. At this time, the subject was given an otoscopic exam and interviewed with regard to hearing condition and history. If no otological problems arose during the exam and the subject claimed no knowledge of such problems, the pure-tone audiogram was performed and evaluated.

Upon meeting the pure-tone threshold criterion, anatomical measurements of the subject were taken. First, the bitragus breadth was measured using a GPM curved, spreading caliper (Figure 24). Second, the ear breadth and



Bitragus breadth

Head height



Ear breadth

Ear length

Figure 24. Anatomical measurements.

ear length (Figure 24) were measured using a DoAll dial caliper. Third, the head height (Figure 24) was measured with a custom-made anthropometer consisting of a T-square and a horizontal head plate mounted to a vertical bar with a sliding collar that locks. Fourth, the ear canal size was measured using the American Optical EARGAGE™. The EARGAGE™ uses five different-sized round balls to obtain a relative measure of the size of the ear canal opening according to 10 different sizes (extra large plus, extra large, large plus, large, medium plus, medium, small plus, small, extra small plus, and extra small). After these measurements were taken, the subject was experience-leveled (if necessary) and the variability test was conducted. After the subject passed all the screening tests, he or she was scheduled for the first experimental session.

<u>Experimental session procedure</u>. Each subject was required to attend 12 experimental sessions, each consisting of three REAT tests (in accordance with ANSI S3.19-1974) per session. In all cases, the experimenter fit the hearing protectors on the subject as per EPA requirements (EPA, 1990). This procedure was expected to reduce the possibility of confounding the results with each subject's differing ability to obtain a good fit. Furthermore, Berger (1982) and Park and Casali (in press[a]) showed that

experimenter-fit conditions generally result in less variability than subject-fit conditions.

Upon arrival for each experimental session, the subject was welcomed and asked if he or she was experiencing any temporary physical conditions which might affect his/her hearing ability (head cold, TTS, headache, etc.). If so, the subject was rescheduled and, if not, the experiment proceeded. The initial condition was always unoccluded, so the subject was first escorted into the chamber, reminded of the experimental procedure, and allowed five minutes to adapt to the environment, after which the first test was conducted. Once the test procedure began, it was conducted in accordance with the REAT method and the Békésy method of tracking, as discussed earlier.

The second session was occluded, so the subject was then escorted out of the chamber, fit with the protector, and escorted back into the chamber. At that time, the subject was reminded of the experimental procedure and presented with a 70-dB white fitting noise. If at any time it was decided by the subject or by the experimenter (through visual inspection) that the seal was lacking, the experimenter refit the hearing protector. This procedure was repeated until both the experimenter and the subject deemed that a "best fit" was obtained. The subject was then allowed two minutes to adjust to the environment, after which the test was conducted. Once a final fit was established and the test had begun, no further adjustment of the HPD was allowed.

The test continued in this manner until three occluded and three unoccluded trials had been obtained, resulting in three attenuation values for each test frequency. The procedure was conducted in the following order: the first trial was unoccluded, the second trial occluded, the third trial occluded, the fourth trial unoccluded, the fifth trial unoccluded, and the sixth trial occluded. After the first trial, only a two-minute accommodation time was required. The subject was paid after the last experimental session.

RESULTS

Introduction

The primary analysis focused on the spectral attenuation, treating each frequency as a different level of a factor in the analysis. Secondary analysis, on the other hand, collapsed attenuation across the frequencies using the NRR calculation method. This method computed a measure called the Noise Reduction Rating Per Subject (NRR_{PS}), which is to be detailed later. All analyses were computed on the IBM 3091 mainframe computer using the Statistical Analysis System (SAS Institute Inc., 1990) and samples were checked through recomputation, either through a different method using SAS or on the Apple Macintosh computer using SuperANOVA, to ensure accuracy (Abascus Concepts, SuperANOVA, 1989).

Trials

As mentioned above, three attenuation measures (called trials) were taken at each frequency for each of the 12 experimental sessions and for each subject. An analysis of variance (ANOVA) technique, with trials as the source of variance and trials-by-subject (within gender) as the denominator, was used to determine if the three trials differed significantly from each other. The results failed to show any significant difference between them ($F = 0.66$, $p = 0.5281$), so the three trials were arithmetically averaged and the average value was used in all subsequent analyses.

Multivariate Analysis of Variance

Multivariate analysis of variance (MANOVA) techniques were considered when conducting the primary analyses of the frequency-specific attenuation data, treating test frequencies as multiple dependent measures. However, this approach was infeasible because the main effect of gender could not be analyzed using MANOVA procedures, due to insufficient degrees of freedom in the denominator. Therefore, univariate analysis of variance procedures were used.

Overall Analysis

The ANOVA table showing sources of variance and F-tests appears in Table 12. The main effects and all interactions of sound-field environment (E), hearing protector (H),

TABLE 12

Results of the ANOVA Summary Table

Source of Variance	df	MS	F[1]	p	G-G p[2]	H-F p[2]
Between						
G	1	21.70	0.450	0.5214		
S/G	8	48.28				
Within						
E	2	1.30	0.158	0.8555		
E*G	2	0.91	0.110	0.8963		
E*S/G	16	8.27				
H	3	1204.04	17.241	0.0001	0.0024	0.0013
H*G	3	54.61	0.782	0.5156		
H*S/G	24	69.84				
F	8	9836.82	663.551	0.0001	0.0001	0.0001
F*G	8	25.13	1.695	0.1168		
F*S/G	64	14.82				
E*H	6	11.08	1.377	0.2430		
E*H*G	6	3.06	0.380	0.8884		
E*H*S/G	48	8.05				
E*F	16	25.84	6.461	0.0001	0.0002	0.0001
E*F*G	16	3.33	0.834	0.6456		
E*F*S/G	128	4.00				
F*H	24	505.75	51.974	0.0001	0.0001	0.0001
F*H*G	24	8.50	0.874	0.6379		
F*H*S/G	192	9.73				
E*F*H	48	4.55	1.556	0.0134	0.1779	0.0311
E*F*H*G	48	1.78	0.610	0.9813		
E*F*H*S/G	384	2.92				
Total	1079					

[1] Denominators used for each source of variance in the *F*-tests appear as the last term in each grouping in the table.

TABLE 12 -- CONTINUED

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[2] Only G-G _p_ and H-F _p_ values appear for those effects in which the original uncorrected _p_ value was significant because the corrections are not useful for nonsignificant effects.

frequency (F), and gender (G) were evaluated using the appropriate F-ratios specified. The Greenhouse-Geisser correction was used to check for sphericity violations and to make the necessary adjustments to the degrees of freedom (Greenhouse and Geisser, 1959). (The reported p values to which the Greenhouse-Geisser correction has been applied are denoted by G-G p, while the p values to which the correction has not been applied are represented by p.) The Huynh-Feldt correction for sphericity violations was performed on selected statistics, but used only as a comparison to the Greenhouse-Geisser correction (Huynh-Feldt corrected p values are symbolized by H-F p; Huynh and Feldt, 1970). Table 13 shows the G-G and the H-F correction epsilons.

Main effects of the factors in the ANOVA that were shown to be significant were further explored through the use of post-hoc tests. These tests can be used to determine which conditions within the main effect differ from each other. In choosing the post-hoc tests, emphasis was placed on those tests that would provide the most sensitivity without unduly inflating the alpha (Type 1) error. The Newman-Keuls procedure was selected because it distributes the alpha error efficiently across the possible comparisons, saving the most power for those comparisons with the smallest differences, while controlling the overall alpha

TABLE 13

Greenhouse-Geisser and Huynh-Feldt Correction Epsilons

Source of Variance	G-G Epsilon	H-F Epsilon
E*S/G	0.9155	1.3219
H*S/G	0.3589	0.4221
F*S/G	0.5204	1.2911
E*H*S/G	0.4373	0.7515
E*F*S/G	0.3011	0.9068
F*H*S/G	0.1347	0.2652
E*F*H*S/G	0.1292	0.6951

error (family-wise error). This point becomes of prime importance when evaluating variables such as the frequency main effect, in which there are 36 comparisons.

For the interactions that showed a significant effect, a "funneling" approach was used to better locate the source of the effect. Simple-effect F-tests were used to explore two-way interactions in further detail, while a simple interaction-effect F-test was used to explore the three-way interaction. The simple-effect F-test distributes the alpha error across only one level of a particular variable, evaluating the other variable at that level to determine significance. When this test proved to be significant for a particular variable level, a Newman-Keuls test was used to determine where the differences between the levels of the other variable were located.

The simple interaction-effect F-test is very similar to the simple-effect F-test, except it distributes the alpha error across one level of a particular variable, while determining significance of the resulting two-way interaction. The two-way interaction that was determined to be significant by this method was then evaluated using the simple-effect F-test described above and followed by a Newman-Keuls test, if appropriate. For both the simple-effect F-test and the simple interaction-effect F-test described above, the denominator used in evaluating significance was the same denominator used to determine overall significance of the original interaction (which will be specified in the discussion of each interaction). The Greenhouse-Geisser correction was used in all simple-effect and simple interaction-effect F-tests and all Newman-Keuls tests.

Interactions

Statistically significant interactions ($p \leq 0.05$) included the E*F interaction ($F = 6.46$, G-G $p = 0.0002$) and the F*H interaction ($F = 51.97$, G-G $p = 0.0001$). Interestingly, the E*F*H interaction was not significant after the Greenhouse-Geisser correction ($F = 1.56$, G-G $p = 0.1779$), but was significant prior to the correction ($p = 0.0134$) and after the Huynh-Feldt correction (H-F $p = 0.0311$). As a result of the inconsistencies between the corrections and strength of the significance prior to the Greenhouse-Geisser correction, a decision was made to study this interaction in further detail. Of course, the reader may choose to adhere to the G-G results, thus disregarding the following discussion on the E*F*H interactions.

Sound-field environment-by-frequency-by-HPD interaction. This interaction was analyzed using the simple interaction-effect *F*-test in only two directions of the possible three. The third direction (the analysis of F*H at levels of E) was believed to be of little interest. (The denominator used in all subsequent analyses of this interaction was $MS_{E*F*H*S/G}$ with 49.6 degrees of freedom.)

In the first direction, frequency was held constant, and the E*H interaction was evaluated at each of the nine frequencies. The results of this evaluation appear in Table 14. In sum, at no frequency was the resultant E*H interaction found significant.

In the second direction, hearing protector was held constant and the E*F interaction was studied for each of the four hearing protectors. The results can be found in Table 15. In sum, for two of the four hearing protectors, the E*F interaction was found to be significant. As a result, simple-effect *F*-tests were conducted for those two hearing protectors.

For the Cabot Safety Model 1720 earmuff, the E*F interaction proved to not be significant. The attenuation for this earmuff appear in Figure 25 and in Table 16.

TABLE 14

Simple Interaction-Effect *F*-Test Results for the Sound-Field Environment-by-Frequency-by-Hearing Protector (E*F*H) Interaction, With Frequency Held Constant

1/3 OB c.f. (Hz)	MS_{E*H}	F[1]	p[2]	G-G p[3]
125	3.902	1.335	0.2406	
250	1.250	0.428	0.8605	
500	7.228	2.472	0.0234	0.1271
1000	3.590	1.228	0.2911	
2000	3.142	1.074	0.3772	
3150	12.562	4.296	0.0003	0.0523
4000	9.501	3.249	0.0040	0.0859
6300	3.389	1.159	0.3276	
8000	2.919	0.998	0.4260	

[1] All *F* ratios were calculated with MSE = 2.924.

[2] All *p* values were calculated with numerator df = 6 and denominator df = 384.

[3] All G-G *p* values were calculated with numerator df = 0.7752 and denominator df = 49.6128. The G-G epsilon used was 0.1292. Only G-G *p* values appear for those effects in which the original uncorrected *p* value was significant because the correction is not useful for nonsignificant effects.

TABLE 15

Simple Interaction-Effect F-Test Results for the Sound-Field Environment-by-Frequency-by-Hearing Protector (E*F*H) Interaction, With Hearing Protector Held Constant

HPD	MS_{E*H}	F[1]	p[2]	G-G p[3]
Model 1720	4.769	1.631	0.0583	
Peltor H9A	10.166	3.477	0.0001	0.0372
Peltor H7A	17.453	5.969	0.0001	0.0044
UltraFit	7.101	2.429	0.0017	0.0969

[1] All F ratios were calculated with MSE = 2.924.

[2] All p values were calculated with numerator df = 16 and denominator df = 384.

[3] All G-G p values were calculated with numerator df = 2.0672 and denominator df = 49.6128. The G-G epsilon used was 0.1292. Only G-G p values appear for those effects in which the original uncorrected p value was significant because the correction is not useful for nonsignificant effects.

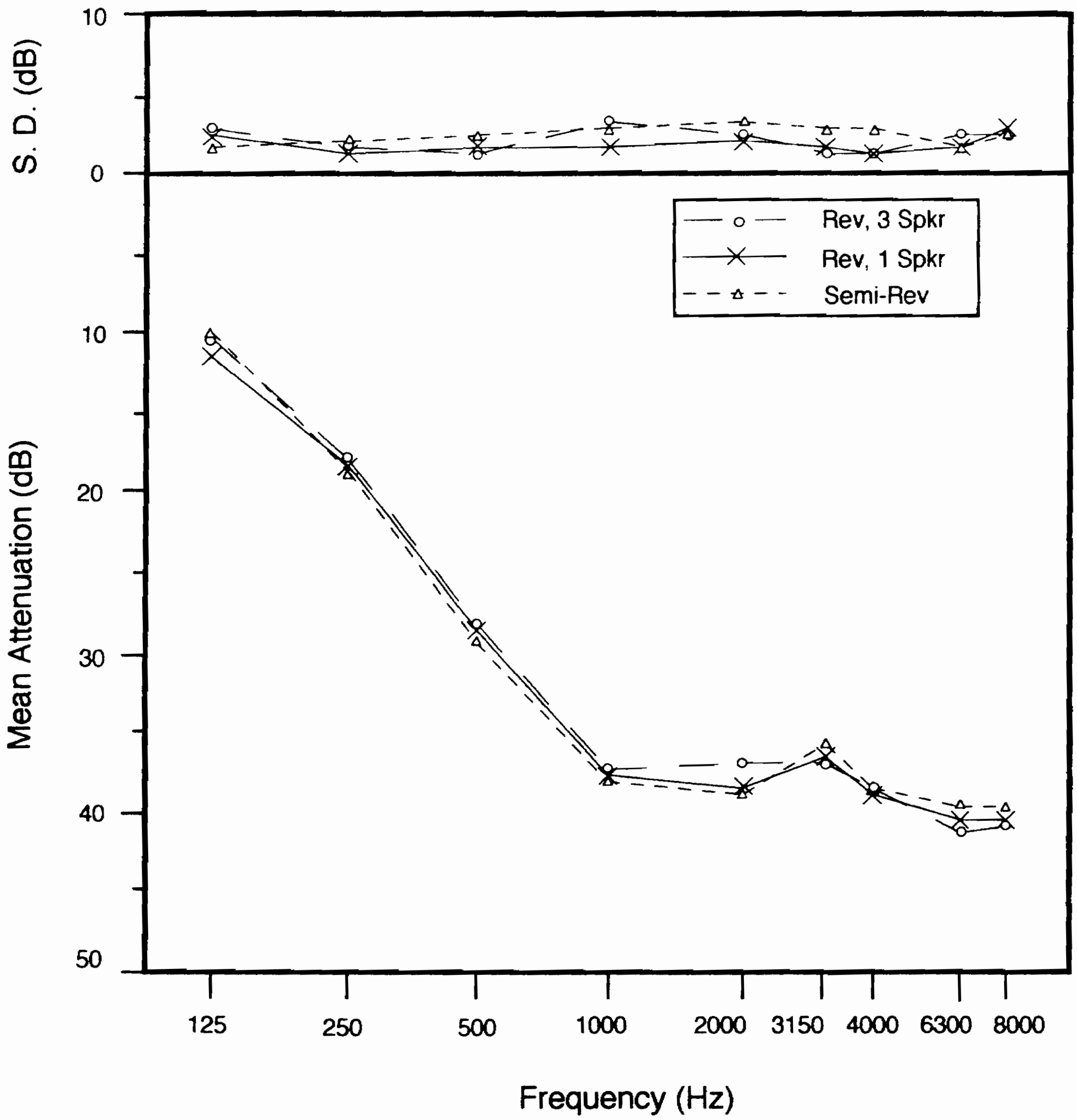


Figure 25. Results of the sound-field environment-by-frequency-by-hearing protector (E*F*H) interaction - Cabot Safety Model 1720 earmuff.

TABLE 16

Results of the Sound-Field Environment-by-Frequency-by-Hearing Protector (E*F*H) Interaction - Cabot Safety Model 1720 Earmuff

1/3 OB c.f.(Hz)	Sound Field	Attenuation (dB)	S. D. (dB)	Significance
125	Rev, 1 Spkr	11.58	2.46	*
	Rev, 3 Spkr	10.36	2.73	*
	Semi-Rev	9.83	1.50	*
250	Semi-Rev	18.55	2.12	*
	Rev, 1 Spkr	18.26	1.32	*
	Rev, 3 Spkr	17.82	1.65	*
500	Semi-Rev	29.34	2.26	*
	Rev, 1 Spkr	28.55	1.70	*
	Rev, 3 Spkr	28.03	1.35	*
1000	Semi-Rev	38.20	2.85	*
	Rev, 1 Spkr	37.58	1.82	*
	Rev, 3 Spkr	37.22	3.18	*
2000	Semi-Rev	38.87	3.23	*
	Rev, 1 Spkr	38.46	2.14	*
	Rev, 3 Spkr	36.95	2.26	*
3150	Rev, 3 Spkr	36.67	1.45	*
	Rev, 1 Spkr	36.48	1.79	*
	Semi-Rev	35.70	2.82	*
4000	Rev, 1 Spkr	38.91	1.33	*
	Rev, 3 Spkr	38.40	1.29	*
	Semi-Rev	38.34	2.78	*
6300	Rev, 3 Spkr	41.28	2.45	*
	Rev, 1 Spkr	40.55	1.76	*
	Semi-Rev	39.67	1.55	*
8000	Rev, 3 Spkr	41.01	2.33	*
	Rev, 1 Spkr	40.43	2.85	*
	Semi-Rev	39.65	2.51	*

* Not applicable; Newman-Keuls test could not be run because interaction was not significant at the G-G $p \leq 0.05$ level.

For the Peltor H9A earmuff, the E*F interaction was significant (_F_ = 3.48, G-G _p_ = 0.0372). Holding frequency constant and evaluating differences across the sound fields resulted in significant differences at 6300 (_F_ = 7.54, G-G _p_ = 0.0353) and 8000 Hz (_F_ = 11.13, G-G _p_ = 0.0182). These two frequencies were further analyzed to determine which sound field differed from each other using the Newman-Keuls test. At both frequencies, the attenuation of the reverberant, three-speaker sound field and the reverberant, one-speaker sound field was significantly greater than that of the semi-reverberant sound field (at 6300 Hz, with differences (Δ) of 2.93 dB and 1.88 dB, respectively; at 8000 Hz, Δ = 3.36 dB and 2.82 dB, respectively), but not significantly different from each other (at 6300 Hz, Δ = 1.05 dB; at 8000 Hz, Δ = 0.54 dB). The results are shown in Figure 26 and Table 17. In these and following tables and figures, levels of the factor with the same letters do not differ significantly from each other at the G-G $p \leq 0.05$ level. In addition, levels of the factor that are not labeled did not show a significant effect in the simple-effect _F_-test.

The E*F interaction for the Peltor H7A earmuff was also significant (_F_ = 5.97, G-G _p_ = 0.0044). Evaluating the differences in the sound fields while holding frequency

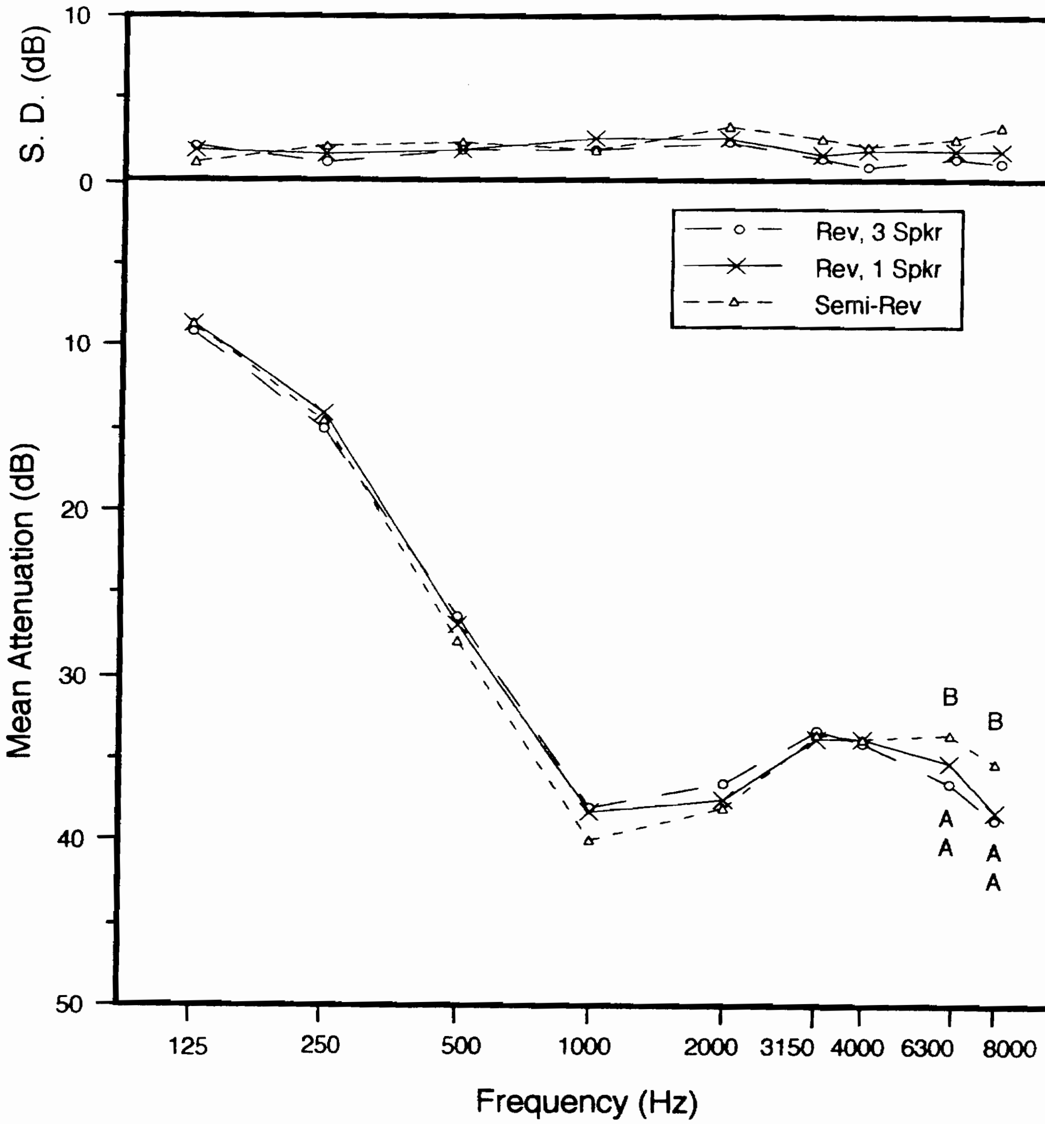


Figure 26. Results of the sound-field environment-by-frequency-by-hearing protector (E*F*H) interaction - Peltor H9A earmuff. (Levels of the sound field factor with the same letters are not significantly different from each other at the G-G $\underline{p} \leq 0.05$ level.)

TABLE 17

Results of the Newman-Keuls Test of the Sound-Field Environment-by-Frequency-by-Hearing Protector (E*F*H) Interaction - Peltor H9A Earmuff

1/3 OB c.f.(Hz)	Sound Field	Attenuation (dB)	S. D. (dB)	Significance[1]
125	Rev, 3 Spkr	9.14	2.24	*
	Rev, 1 Spkr	8.84	1.95	*
	Semi-Rev	8.69	1.12	*
250	Rev, 3 Spkr	15.12	1.18	*
	Rev, 1 Spkr	14.07	1.56	*
	Semi-Rev	14.52	2.13	*
500	Semi-Rev	27.88	2.44	*
	Rev, 1 Spkr	26.88	1.86	*
	Rev, 3 Spkr	26.33	1.85	*
1000	Semi-Rev	39.88	2.03	*
	Rev, 1 Spkr	38.20	2.55	*
	Rev, 3 Spkr	37.90	1.96	*
2000	Semi-Rev	37.92	3.43	*
	Rev, 1 Spkr	37.53	2.61	*
	Rev, 3 Spkr	36.40	2.44	*
3150	Rev, 1 Spkr	33.81	1.57	*
	Semi-Rev	33.45	2.54	*
	Rev, 3 Spkr	33.21	1.41	*
4000	Rev, 3 Spkr	34.01	0.90	*
	Semi-Rev	33.71	2.15	*
	Rev, 1 Spkr	33.67	1.81	*
6300	Rev, 3 Spkr	36.38	1.37	A
	Rev, 1 Spkr	35.33	1.88	A
	Semi-Rev	33.45	2.59	B
8000	Rev, 3 Spkr	38.68	1.11	A
	Rev, 1 Spkr	38.14	1.77	A
	Semi-Rev	35.32	3.34	B

* Not applicable, Newman-Keuls test could not be run because interaction was not significant at this frequency.

[1] Levels of the sound field factor with the same letters are not significantly different from each other.

constant, this interaction showed significant differences at 1000 (F = 8.28, G-G p = 0.0306), 3150 (F = 15.48, G-G p = 0.0088), 4000 (F = 9.45, G-G p = 0.0245), and 8000 Hz (F = 7.69, G-G p = 0.0342). The Newman-Keuls test was used to analyze further these frequencies, the results of which can be seen in Figure 27 and Table 18. Again, levels of the sound field with the same letter do not differ significantly from each other at the G-G $p \leq 0.05$ level and levels that are not labeled did not show significance in the simple-effect F-test.

At 1000 Hz and 4000 Hz, the semi-reverberant sound field resulted in a significantly greater attenuation than both the reverberant, one-speaker (at 1000 Hz, Δ = 2.24 dB; at 4000 Hz, Δ = 2.38 dB) and the reverberant, three-speaker (at 1000 Hz, Δ = 2.99 dB; at 4000 Hz, Δ = 3.20 dB), which did not differ significantly from each other (at 1000 Hz, Δ = 0.75 dB; at 4000 Hz, Δ = 0.82 dB). At 3150 Hz, the semi-reverberant sound field again resulted in significantly greater attenuation than the reverberant, one-speaker sound field (Δ = 1.94 dB), and both resulted in significantly greater attenuation than the reverberant, three-speaker sound field (Δ = 4.25 dB and 2.31 dB, respectively). However, at 8000 Hz the trend reversed. The reverberant, three-speaker sound field resulted in greater attenuation

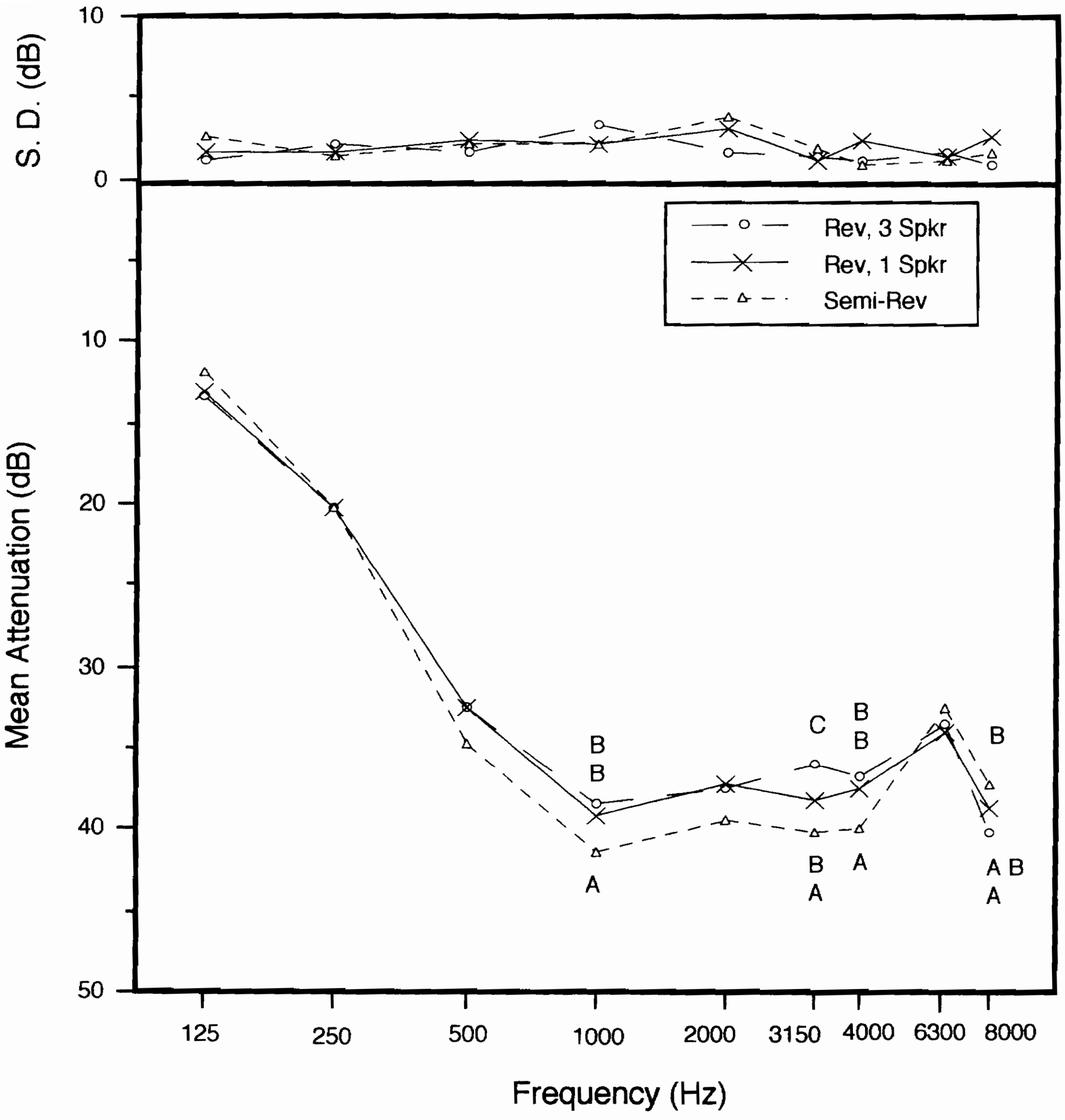


Figure 27. Results of the sound-field environment-by-frequency-by-hearing protector (E*F*H) interaction - Peltor H7A earmuff. (Levels of the sound field factor with the same letters are not significantly different from each other at the G-G $\underline{p} \leq 0.05$ level.)

TABLE 18

Results of the Newman-Keuls Test of the Sound-Field Environment-by-Frequency-by-Hearing Protector (E*F*H) Interaction - Peltor H7A Earmuff

1/3 OB c.f. (Hz)	Sound Field	Attenuation (dB)	S. D. (dB)	Significance[1]
125	Rev, 3 Spkr	13.31	1.21	*
	Rev, 1 Spkr	13.13	1.72	*
	Semi-Rev	11.78	2.45	*
250	Rev, 3 Spkr	20.30	2.21	*
	Semi-Rev	20.21	1.42	*
	Rev, 1 Spkr	20.16	1.71	*
500	Semi-Rev	34.71	2.18	*
	Rev, 1 Spkr	32.60	2.35	*
	Rev, 3 Spkr	32.48	1.62	*
1000	Semi-Rev	41.34	2.23	A
	Rev, 1 Spkr	39.10	2.16	B
	Rev, 3 Spkr	38.35	3.26	B
2000	Semi-Rev	39.49	3.95	*
	Rev, 3 Spkr	37.42	1.69	*
	Rev, 1 Spkr	37.19	3.04	*
3150	Semi-Rev	40.19	1.95	A
	Rev, 1 Spkr	38.25	1.23	B
	Rev, 3 Spkr	35.94	1.47	C
4000	Semi-Rev	39.78	0.87	A
	Rev, 1 Spkr	37.40	2.31	B
	Rev, 3 Spkr	36.58	1.19	B
6300	Rev, 1 Spkr	33.99	1.36	*
	Rev, 3 Spkr	33.51	1.63	*
	Semi-Rev	32.49	1.21	*
8000	Rev, 3 Spkr	40.10	1.04	A
	Rev, 1 Spkr	38.60	2.46	A B
	Semi-Rev	37.10	1.73	B

* Not applicable, Newman-Keuls test could not be run because interaction was not significant at this frequency.

[1] Levels of the sound field factor with the same letters are not significantly different from each other.

than the semi-reverberant sound field ($\Delta = 3.00$ dB), but neither differed significantly from the reverberant, one-speaker sound field ($\Delta = 1.50$ and 1.50 dB, respectively).

For the UltraFit earplug, the E*F interaction did not show significance. Figure 28 and Table 19 show the attenuation and results for this earplug.

Sound-field environment-by-frequency interaction. The three-way interaction (E*F*H) provided more detailed information regarding how sound-field environment and frequency interact, showing that the interaction was different for the different types of hearing protectors. However, because of the discrepancy in significance between the G-G and the H-F results on the three-way interaction, the two-way interaction was evaluated in further detail. (The denominator used in all subsequent analyses of this interaction was $MS_{E*F*S\backslash G}$ with 38.5 degrees of freedom.)

A simple-effect F-test showed that the sound fields differed from each other at 1000 ($F = 7.93$, G-G $p = 0.0052$), 2000 ($F = 7.82$, G-G $p = 0.0055$), 6300 ($F = 8.64$, G-G $p = 0.0036$), and 8000 Hz ($F = 16.06$, G-G $p = 0.0001$) (Table 20). The Newman-Keuls test was used to further evaluate these four frequencies. At 1000 and 2000 Hz, the semi-reverberant sound field was shown to have significantly greater

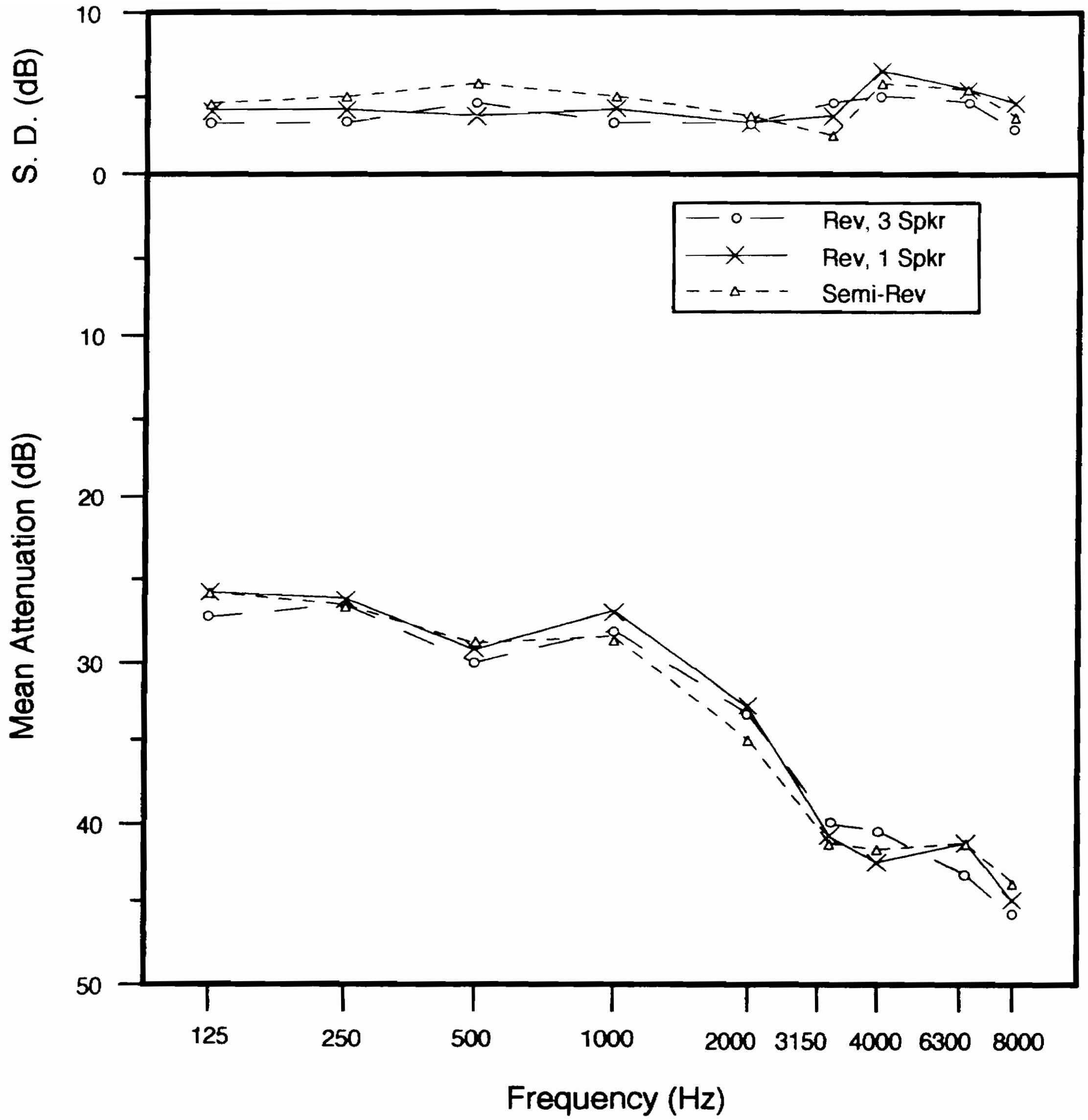


Figure 28. Results of the sound-field environment-by-frequency-by-hearing protector (E*F*H) interaction - E-A-R UltraFit earplug.

TABLE 19

Results of the Sound-Field Environment-by-Frequency-by-Hearing Protector (E*F*H) Interaction - UltraFit Earplug

1/3 OB c.f.(Hz)	Sound Field	Attenuation (dB)	S. D. (dB)	Significance
125	Rev, 3 Spkr	27.18	3.26	*
	Semi-Rev	25.90	4.45	*
	Rev, 1 Spkr	25.73	4.14	*
250	Rev, 3 Spkr	26.69	3.45	*
	Semi-Rev	26.37	4.72	*
	Rev, 1 Spkr	26.17	4.02	*
500	Rev, 3 Spkr	30.31	4.28	*
	Rev, 1 Spkr	29.35	3.85	*
	Semi-Rev	28.83	5.75	*
1000	Semi-Rev	28.46	4.98	*
	Rev, 3 Spkr	27.97	3.05	*
	Rev, 1 Spkr	27.14	3.87	*
2000	Semi-Rev	34.79	3.84	*
	Rev, 3 Spkr	33.40	3.45	*
	Rev, 1 Spkr	33.09	3.12	*
3150	Semi-Rev	41.16	2.59	*
	Rev, 1 Spkr	40.83	3.63	*
	Rev, 3 Spkr	40.24	4.29	*
4000	Rev, 1 Spkr	42.44	6.30	*
	Semi-Rev	41.64	5.77	*
	Rev, 3 Spkr	40.36	5.03	*
6300	Rev, 3 Spkr	43.12	4.50	*
	Rev, 1 Spkr	41.44	5.27	*
	Semi-Rev	41.29	5.17	*
8000	Rev, 3 Spkr	45.75	2.89	*
	Rev, 1 Spkr	44.68	4.38	*
	Semi-Rev	43.45	3.83	*

* Not applicable, Newman-Keuls test could not be run because interaction was not significant.

TABLE 20

Simple-Effect F-Test Results For Sound-Field Environment-by-Frequency (E*F) Interaction

1/3 OB c.f. (Hz)	MS_{E*F}	F[1]	p[2]	G-G p[3]
125	10.148	2.538	0.0828	
250	1.113	0.278	0.7562	
500	10.212	2.554	0.0820	
1000	31.729	7.934	0.0006	0.0052
2000	31.275	7.821	0.0006	0.0055
3150	13.311	3.329	0.0389	0.0686
4000	11.459	2.865	0.0603	
6300	34.559	8.642	0.0003	0.0036
8000	64.202	16.055	0.0001	0.0001

[1] All F ratios were calculated with MSE = 3.999.

[2] All p values were calculated with numerator df = 2 and denominator df = 128.

[3] All G-G p values were calculated with numerator df = 1.2044 and denominator df = 38.5408. The G-G epsilon used was 0.3011. Only G-G p values appear for those effects in which the original uncorrected p value was significant because the correction is not useful for nonsignificant effects.

attenuation than the reverberant, one-speaker sound field (at 1000 Hz, Δ = 1.46 dB; at 2000 Hz, Δ = 1.20 dB) and the reverberant, three-speaker sound field (at 1000 Hz, Δ = 1.60 dB; at 2000 Hz, Δ = 1.73 dB). No significant differences were shown to exist between the latter two sound fields for either of these two frequencies (at 1000 Hz, Δ = 0.15 dB; at 2000 Hz, Δ = 0.53 dB).

At 6300 Hz, the trend reversed. The reverberant, three-speaker sound field showed greater attenuation than the semi-reverberant sound field (Δ = 1.84 dB), but not greater attenuation than the reverberant, one-speaker condition (Δ = 0.75 dB). In addition, the reverberant, one-speaker sound field showed greater attenuation than the semi-reverberant sound field (Δ = 1.10 dB). The results at 8000 Hz showed the reverberant, three-speaker sound field with greater attenuation than the reverberant, one-speaker sound field (Δ = 0.93 dB) and the semi-reverberant sound field (Δ = 2.51 dB). The latter two also differed significantly from each other (Δ = 1.58 dB). Figure 29 and Table 21 show the results of these analyses, with levels of sound field which do not differ significantly from each other at the G-G $\underline{p} \leq 0.05$ level being assigned the same letters.

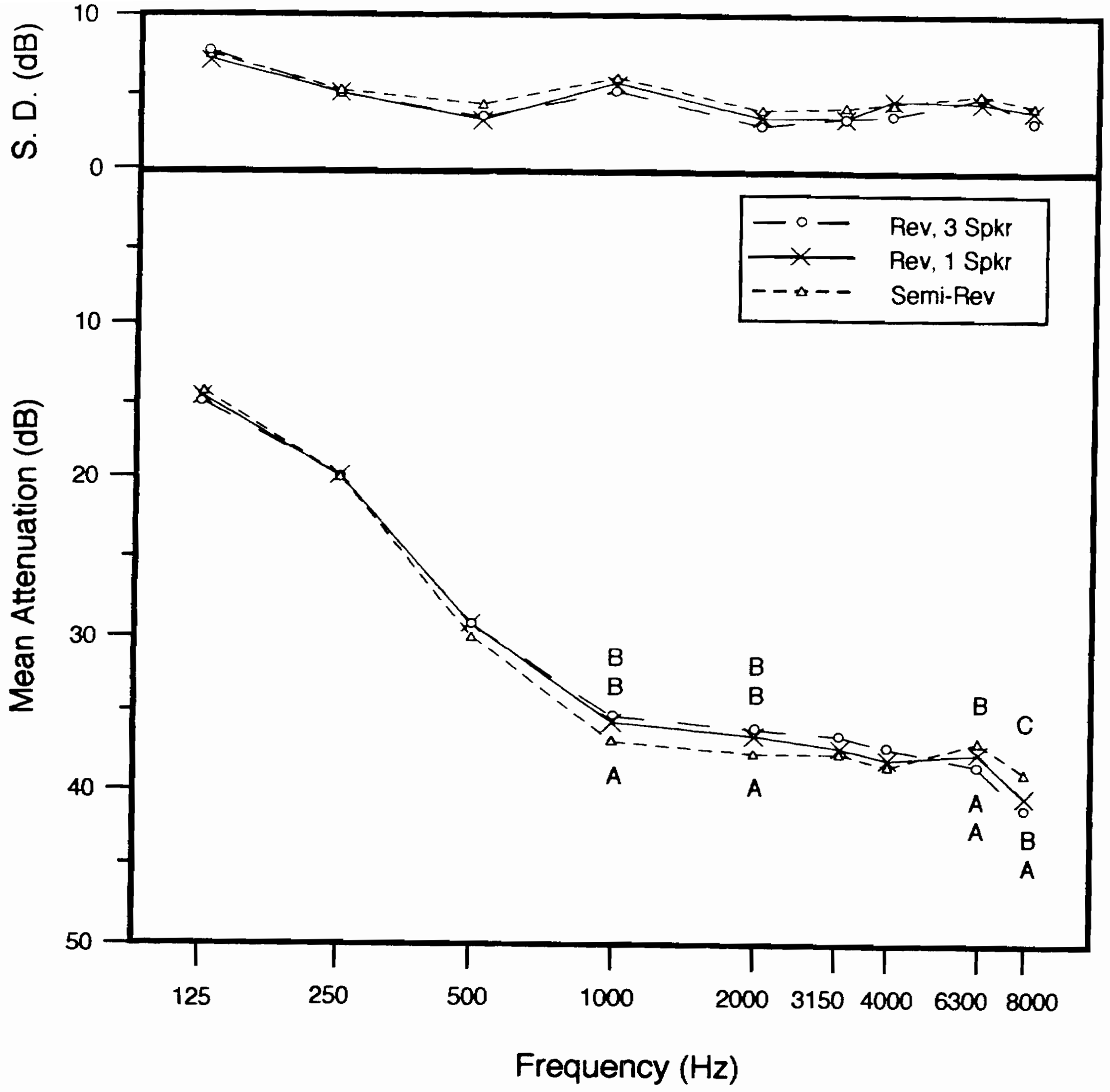


Figure 29. Results of the Newman-Keuls test for the sound-field environment-by-frequency (E*F) interaction. (Levels of the sound field factor with the same letters are not significantly different from each other at the G-G $p \leq 0.05$ level.)

TABLE 21

Results of the Newman-Keuls Test For The Sound-Field Environment-by-Frequency (E*F) Interaction

1/3 OB c.f.(Hz)	Sound Field	Attenuation (dB)	S. D. (dB)	Significance[1]
125	Rev, 3 Spkr	15.00	7.67	*
	Rev, 1 Spkr	14.82	7.07	*
	Semi-Rev	14.05	7.49	*
250	Rev, 3 Spkr	19.98	4.86	*
	Semi-Rev	19.91	5.13	*
	Rev, 1 Spkr	19.67	4.98	*
500	Semi-Rev	30.19	4.31	*
	Rev, 1 Spkr	29.35	3.26	*
	Rev, 3 Spkr	29.29	3.40	*
1000	Semi-Rev	36.97	5.98	A
	Rev, 1 Spkr	35.51	5.57	B
	Rev, 3 Spkr	35.36	5.16	B
2000	Semi-Rev	37.77	3.93	A
	Rev, 1 Spkr	36.57	3.37	B
	Rev, 3 Spkr	36.04	2.91	B
3150	Semi-Rev	37.63	4.01	*
	Rev, 1 Spkr	37.34	3.38	*
	Rev, 3 Spkr	36.52	3.48	*
4000	Semi-Rev	38.37	4.42	*
	Rev, 1 Spkr	38.11	4.66	*
	Rev, 3 Spkr	37.34	3.52	*
6300	Rev, 3 Spkr	38.57	4.70	A
	Rev, 1 Spkr	37.83	4.36	A
	Semi-Rev	36.73	4.85	B
8000	Rev, 3 Spkr	41.39	3.31	A
	Rev, 1 Spkr	40.46	3.91	B
	Semi-Rev	38.88	4.20	C

* Not applicable, Newman-Keuls test could not be run because interaction was not significant at this frequency.

[1] Levels of the sound field factor with the same letters are not significantly different from each other.

This interaction was also analyzed to determine if it would preclude the interpretation of the frequency main effect. As seen in Figure 30, a few of the frequencies were ordinal (relative positioning does not change) with respect to all other frequencies, namely 125, 250, 500, and 8000 Hz. The attenuation at 1000 Hz was ordinal with respect to all frequencies, except 6300 Hz, and 4000 Hz was ordinal with respect to all frequencies, except 6300 Hz. No other ordinal relationships existed for this interaction. The main effect of frequency can only be interpreted between frequencies in which there is an ordinal relationship.

Frequency-by-HPD interaction. The F*H interaction proved to be highly significant. However, this was to be expected. It is a well-known fact that the attenuation of different hearing protectors will vary comparatively across different frequencies, some showing greater attenuation at the low frequencies and others showing greater attenuation at the high frequencies, for example. This can result from a host of factors, including HPD design differences, quality of fit, subject's anthropometric features, among others. The simple-effect F-test was used to determine at what frequencies the hearing protector variable was significant, and significance was shown at every frequency (Table 22). The Newman-Keuls test was used to evaluate those significant

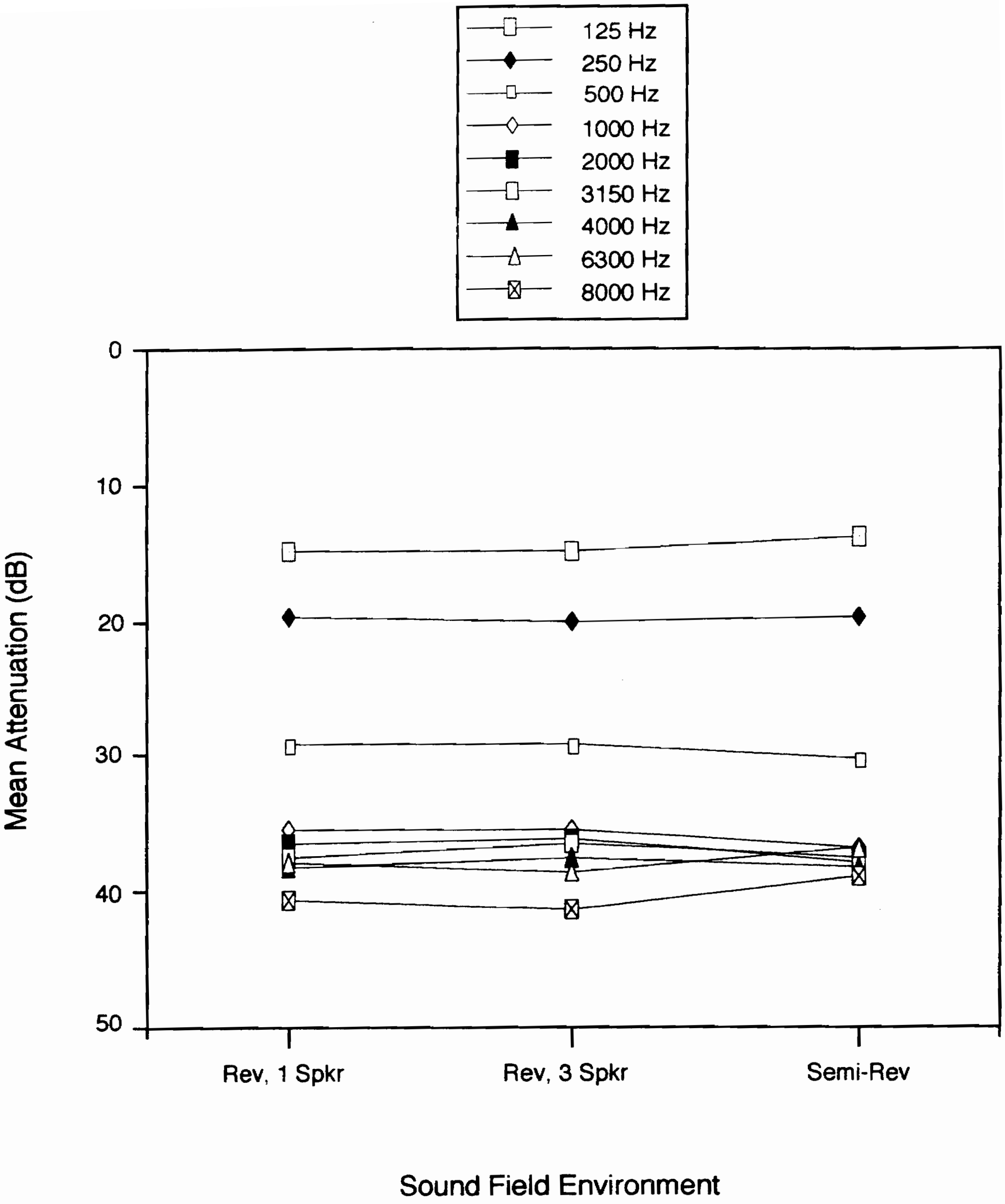


Figure 30. Graph of the environment-by-frequency (E*F) interaction.

TABLE 22

Simple Effect F-Test Results For Frequency-by-Hearing Protector (F*H) Interaction

1/3 OB c.f. (Hz)	MS_{E*H}	F^1	p^2	G-G p^3
125	1883.307	193.539	0.0001	0.0001
250	737.409	75.780	0.0001	0.0001
500	209.570	21.537	0.0001	0.0001
1000	890.912	91.555	0.0001	0.0001
2000	126.688	13.019	0.0001	0.0015
3150	280.122	28.787	0.0001	0.0001
4000	300.713	30.903	0.0001	0.0001
6300	520.040	53.442	0.0001	0.0001
8000	301.272	30.960	0.0001	0.0001

[1] All F ratios were calculated with MSE = 9.731.

[2] All p values were calculated with numerator df = 3 and denominator df = 192.

[3] All G-G p values were calculated with numerator df = 0.7959 and denominator df = 50.9184. The G-G epsilon used was 0.2652.

HPD variables in further detail, the results of which can be seen in Figure 31 and Table 23. Levels of the HPD factor with the same letters did not result in significantly different attenuation at the G-G $\underline{p} \leq 0.05$ level. (The denominator used in all subsequent analyses of this interaction was $MS_{H*F*S\backslash G}$ with 50.9 degrees of freedom.)

As can be seen in Figure 31, the interactions with HPD were disordinal and therefore interfere with the interpretation of the main effect (Keppel, 1982). The UltraFit earplug at some frequencies resulted in significantly greater attenuation than the three earmuffs and at some frequencies resulted in significantly less attenuation than the three earmuffs. Therefore, few conclusions can be drawn concerning its main effect. Similar statements can be made concerning all other relationships among these hearing protectors. No single hearing protector resulted in greater attenuation at all frequencies than another hearing protector. As a result, they were disordinal, and conclusions regarding the main effect of hearing protector cannot be interpreted independently of this interaction. It is interesting to note, however, that the one earplug tested showed greater attenuation at the low frequencies, less attenuation at the middle frequencies, and greater attenuation at the high

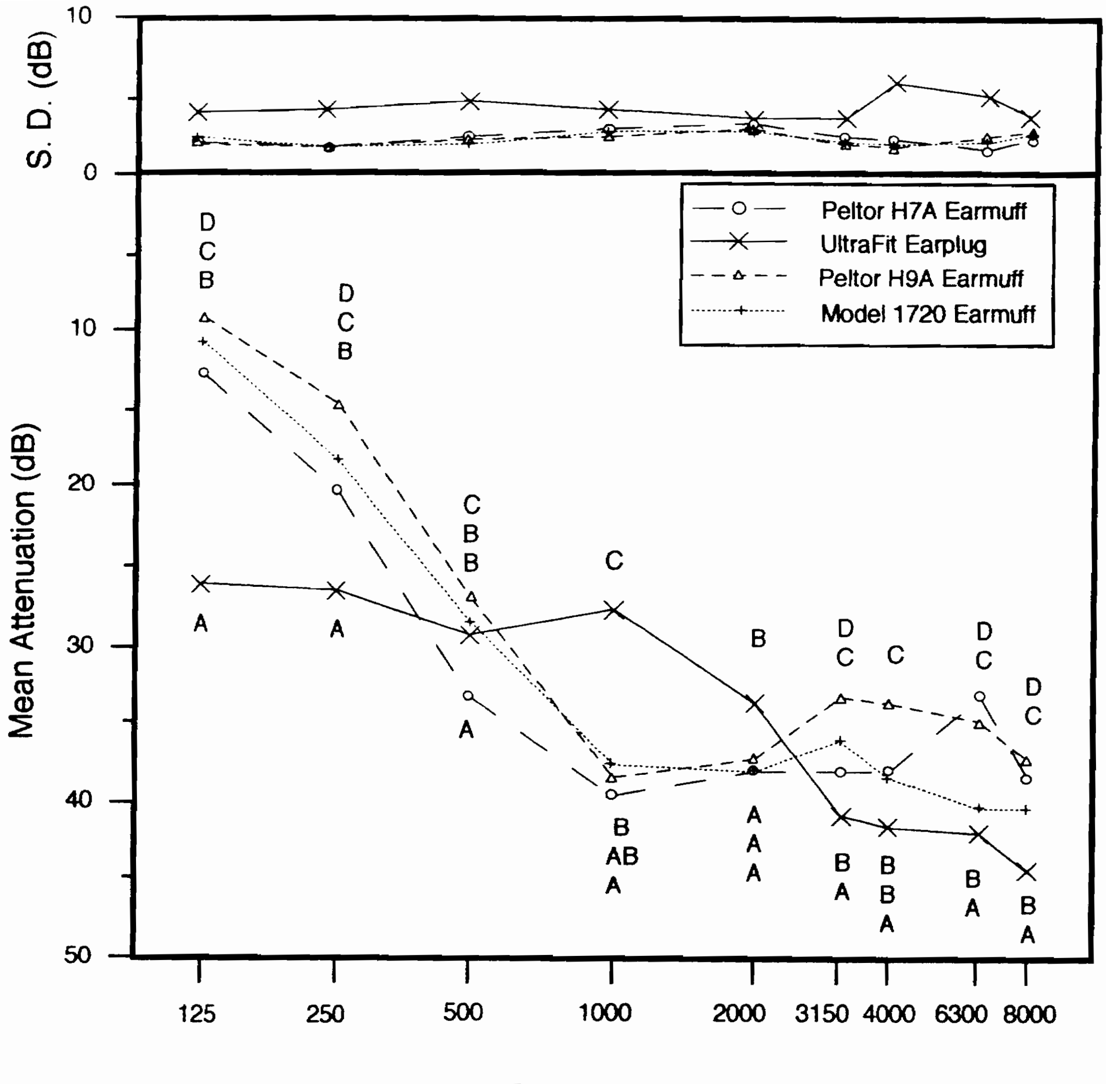


Figure 31. Results of the Newman-Keuls test for the frequency-by-hearing protector (F*H) interaction. (Levels of the hearing protector factor with the same letters are not significantly different from each other at the G-G $\underline{p} \leq 0.05$ level.)

TABLE 23

Results of the Newman-Keuls Test for the Frequency-by-Hearing Protector (F*H) Interaction

1/3 OB c.f.(Hz)	Hearing Protector	Attenuation (dB)	S. D. (dB)	Significance[1]
125	UltraFit	26.27	3.90	A
	Peltor H7A	12.74	1.93	B
	Model 1720	10.59	2.33	C
	Peltor H9A	8.89	1.78	D
250	UltraFit	26.41	3.96	A
	Peltor H7A	20.22	1.75	B
	Model 1720	18.21	1.69	C
	Peltor H9A	14.57	1.67	D
500	Peltor H7A	33.26	2.26	A
	UltraFit	29.50	4.57	B
	Model 1720	28.64	1.83	B
	Peltor H9A	27.03	2.10	C
1000	Peltor H7A	39.60	2.82	A
	Peltor H9A	38.66	2.30	A B
	Model 1720	37.67	2.62	B
	UltraFit	27.86	3.94	C
2000	Model 1720	38.09	2.64	A
	Peltor H7A	38.03	3.11	A
	Peltor H9A	37.28	2.84	A
	UltraFit	33.76	3.44	B
3150	UltraFit	40.74	3.46	A
	Peltor H7A	38.13	2.33	B
	Model 1720	36.28	2.07	C
	Peltor H9A	33.49	1.85	D
4000	UltraFit	41.48	5.59	A
	Model 1720	38.55	1.88	B
	Peltor H7A	37.92	2.06	B
	Peltor H9A	33.80	1.65	C
6300	UltraFit	41.95	4.89	A
	Model 1720	40.50	2.00	B
	Peltor H9A	35.05	2.30	C
	Peltor H7A	33.33	1.50	D

TABLE 23 -- CONTINUED

8000	UltraFit	44.63	3.74	A
	Model 1720	40.36	2.55	B
	Peltor H7A	38.60	2.17	C
	Peltor H9A	37.38	2.66	D

[1] Levels of the hearing protector factor with the same letters are not significantly different from each other.

frequencies than all three earmuffs, which were relatively close to each other.

This interaction was also examined to determine if it interfered with the interpretation of the frequency main effect. Figure 32 shows that 125 and 250 Hz were still ordinal with respect to all other frequencies. Five hundred Hz was ordinal with all frequencies except 1000 Hz, and 8000 Hz was ordinal with all frequencies except 1000 Hz and 6300 Hz. No other ordinal relationships existed in this interaction.

Main Effects

HPD main effect. The main effect of hearing protector was shown to be significant. The Newman-Keuls test was used to determine which hearing protectors differed from each other. The result of this analysis is shown in Table 24. In sum, the UltraFit earplug showed significantly greater attenuation (34.73 dB) than any of the three earmuffs. The Peltor H7A and the Model 1720 showed significantly greater attenuation (32.43 dB and 32.10 dB, respectively) than the Peltor H9A (29.57 dB), but did not differ significantly from each other. These results should not be interpreted independently of the F*H interaction, for it was shown there

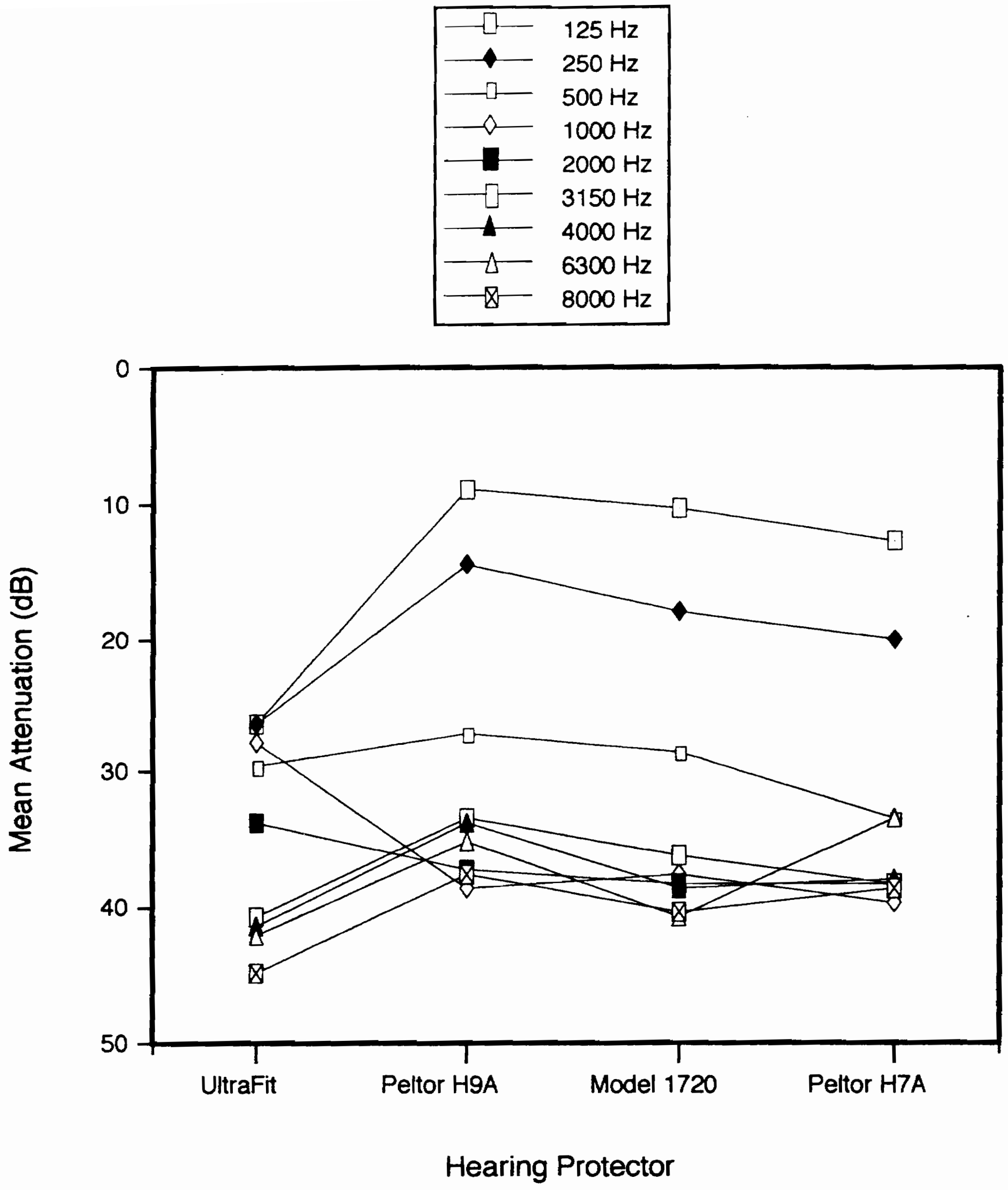


Figure 32. Graph of the frequency-by-hearing protector (F*H) interaction.

TABLE 24

Results of the Newman-Keuls Test for the Hearing Protector Main Effect

Hearing Protector	Attenuation (dB)	S. D. (dB)	Significant[1]
UltraFit	34.73	8.20	A
Peltor H7A	32.43	9.24	B
Model 1720	32.10	10.43	B
Peltor H9A	29.57	10.38	C

[1] Levels of the hearing protector factor with the same letters are not significantly different from each other at the G-G $p \leq 0.05$ level.

that the results would differ depending upon the frequency tested. In addition, this outcome is of little surprise and little interest, since it is well-known that hearing protectors vary in attenuation.

Frequency. Based on the significant frequency ANOVA main effect, a Newman-Keuls test was used to determine which frequencies differed from each other, and the results can be seen in Table 25. In this table, frequencies with same letters do not differ significantly from each other at the G-G $p \leq 0.05$ level. Again, these results cannot be interpreted independently of the H*F and the E*F interaction. These interactions show that the relationships among the frequencies will change, depending upon the hearing protector tested and the environment in which the test took place. Only 125 and 250 Hz were completely independent of these factors. The relationship between 500 Hz and 1000 Hz could not be interpreted independently of the hearing protector tested, but all other relationships with 500 Hz could. The hearing protector tested also affected the relationship between 8000 Hz and 1000 Hz and between 8000 Hz and 6300 Hz, but did not affect any other relationships with 8000 Hz.

TABLE 25

Results of the Newman-Keuls Test for the Frequency Main Effect

1/3 OB c.f. (Hz)	Attenuation (dB)	S. D. (dB)	Significant[1]
8000	40.24	3.93	A
4000	37.94	4.21	B
6300	37.71	4.66	B
3150	37.16	3.63	B C
2000	36.79	3.48	B C
1000	35.95	5.58	C
500	29.61	3.68	D
250	19.85	4.95	E
125	14.62	7.36	F

[1] Levels of the frequency factor with the same letters are not significantly different from each other at the G-G $\underline{p} \leq 0.05$ level.

NRR Per Subject - Secondary Analysis

A new measure, called the NRR per subject (NRR_{PS}), was devised to allow statistical inferences to be made concerning a measure which has a stronger relation to the NRR. For this measure, an NRR_{PS} was calculated for each subject for each experimental condition. The calculations were the same as for the NRR discussed previously, except that only one subject and one trial constituted the data set so the two standard deviation correction could not be applied. The 3-dB spectral uncertainty correction was, however, utilized. Therefore, these values cannot be substituted on a one-to-one basis for the conventional NRR. However, they do allow statistical comparisons to be made.

The ANOVA summary table of results appears in Table 26 and the resultant Greenhouse-Geisser and Huynh-Feldt epsilons appear in Table 27. From Table 26, only the main effect of hearing protector was significant ($F = 19.98$, G-G $p = 0.010$). A Newman-Keuls analysis was performed and showed that the Peltor H7A earmuff (29.12 dB) and the UltraFit earplug (28.91 dB) had significantly greater attenuation than Model 1720 earmuff (27.23 dB) which, in turn, had significantly greater attenuation than the Peltor H9A earmuff (24.66 dB) at the G-G $p \leq 0.05$ level (Table 28).

TABLE 26

Results of the ANOVA summary table for the NRR_{PS}

Source of Variance	df	MS	F[1]	p	G-G p[2]	H-F p[2]
Between						
G	1	7.55	2.915	0.1262		
S/G	8	2.59				
Within						
E	2	0.14	0.073	0.9321		
E*G	2	0.23	0.120	0.8892		
E*S/G	16	1.91				
H	3	127.50	19.984	0.0001	0.0010	0.0003
H*G	3	1.71	0.268	0.8480		
H*S/G	24	6.38				
E*H	6	1.29	0.617	0.7170		
E*H*G	6	1.07	0.512	0.7963		
E*H*S/G	48	2.09				

[1] Denominators used for each source of variance in the F tests appear as the last term in each grouping in the table.

[2] Only G-G p and H-F p values appear for those effects in which the original uncorrected p value was significant because the corrections are not useful for nonsignificant effects.

TABLE 27

Greenhouse-Geisser and Huynh-Feldt correction epsilons for NRR_{PS}

Source of Variance	G-G Epsilon	H-F Epsilon
E*S/G	0.7901	1.0750
H*S/G	0.4003	0.4908
E*H*S/G	0.4202	0.7061

TABLE 28

Results of the Newman-Keuls Test for the Hearing Protector Main Effect of the NRR_{PS}

Hearing Protector	NRR_{PS} (dB)	S. D. (dB)	Significant[1]
Peltor H7A	29.12	1.23	A
UltraFit	28.91	2.60	A
Model 1720	27.23	1.40	B
Peltor H9A	24.66	1.12	C

[1] Levels of the hearing protector factor with the same letters are not significantly different from each other.

DISCUSSION

The objectives of this research were (1) to determine if the requirement of a random-incidence, completely diffuse sound field for the testing of hearing protection devices is necessary and to ascertain if modifications to the diffusivity requirement of ANSI S3.19-1974 should be allowed, and (2) to determine if the environment's diffusivity affects attenuation values depending upon the type of HPD used. Each of these objectives was met and is discussed in further detail.

Effect of Diffusivity on Specific Hearing Protectors

Whether or not the effects of the sound field differ significantly for the different types of hearing protector depends primarily on the reader's interpretation of the sound-field environment-by-frequency-by-hearing protector (E*F*H) interaction, for which there was disagreement between the Greenhouse-Geisser and the Huynh-Feldt corrections. If the interaction is considered as non-significant, one would conclude that the effect of the sound field does not differ depending upon the hearing protector.

If the interaction is believed to be significant, further conclusions can be drawn.

The three sound fields did not have a significantly different effect on the attenuation measured for the Cabot Safety Model 1720 earmuff or the E-A-R UltraFit earplug at any of the frequencies tested (Tables 16 and 19). This result, in itself, is of interest. It was hypothesized that the sound fields tested would not show a significant effect for the earplug because there was no significant effect of sound field for earplugs when more extreme conditions were tested (i.e., highly directional anechoic vs. diffuse reverberant sound fields) (Berger, 1985a; Bolka, 1972; Whittle and Robinson, 1977).

However, it was thought that if leaks in the protector were at the root of the reported difference between the extreme conditions, the Model 1720 earmuff would likely show a difference between the sound fields tested in this study because it was difficult to fit and thus was likely to have leaks. Yet, such a difference was not shown in the data (Table 16). One explanation is that the Model 1720 air leaks did not exist in the experimental data due, in part, to the fitting techniques. This earmuff was adjustable in several dimensions and since the earmuff was fit by experienced, trained experimenters, it is possible that the air leaks were overcome due to the fitting techniques. A highly adjustable earmuff when fit by a trained person can be an asset, but when fit by an inexperienced, untrained person can become a liability. Apparently, in this experiment, it was an asset.

The sound fields did, however, have a significantly different effect on the Peltor H9A earmuff and the Peltor H7A earmuff, both of which had minimal adjustment features. The Peltor H9A showed a significant effect at only two frequencies (Table 17). The Peltor H7A showed a stronger effect, with significance at four frequencies (Table 18). In examining these differences, it is perhaps best to compare the two degraded sound fields to the reverberant, three-speaker sound field, since it is this latter sound field that is specified in the ANSI S3.19-1974 standard and the other two are simply variations of it which do not fully meet the standard.

In the low frequencies (125, 250, and 500 Hz), no significant effects were found. This result is believed to be due to the fact that low frequencies diffract around objects, thus entering the muff through an existent air leak, whether the field is diffuse or directional.

In the middle frequencies (1000, 3150, and 4000 Hz), the Peltor H7A was the only earmuff to show significant effects. In these frequencies, the result was as originally hypothesized: the semi-reverberant sound field resulted in greater attenuation than the reverberant, three-speaker sound field (Δ = 2.99 dB, 4.25 dB, and 3.20 dB, respectively). At 3150 Hz, the reverberant, one-speaker sound field also showed greater attenuation than the reverberant, three-speaker sound field (Δ = 2.31 dB). These results are believed to be due to the diffuse signal characteristics of the reverberant, three-speaker sound field being able to "find" the air leak, while these leaks have a greater possibility of being shielded from the more directional reverberant, one-speaker sound field and semi-reverberant sound field. Of course, these middle frequencies show less diffraction than the aforementioned low frequencies.

At the high frequencies (6300 and 8000 Hz) the trend reversed, with the reverberant, three-speaker sound field exhibiting greater attenuation than the semi-reverberant sound field (for Peltor H9A at 6300 Hz, Δ = 2.93 dB; for Peltor H9A at 8000 Hz, Δ = 3.36 dB; for Peltor H7A at 8000 Hz, Δ = 3.00 dB) and no significant difference with the reverberant, one-speaker sound field. Both the Peltor H9A and the Peltor H7A earmuff showed this effect, although the Peltor H7A showed significance only at 8000 Hz. This shift in trend is in accordance with that found by Whittle and Robinson (1977). Berger (1975) and Bolka (1972) also showed a similar trend, although they did not report significant differences.

Diffusivity - General Trends Across Sound Fields

The sound field in which the hearing protectors are tested can have a significant effect on the attenuation measured, according to the sound-field environment-by-frequency (E*F) interaction (Table 21). (It should again be noted that this interaction results in less information and therefore is of little interest if the E*F*H interaction is assumed to be significant, for the reasons discussed previously.) However, the magnitude and direction of this effect depended upon the frequency tested. For low frequencies (125, 250, and 500 Hz), no significant effects between the sound fields were found. As stated above, this result is believed to be due to the fact that low frequency signals tend to bend around objects and find the air leaks in a protector, apparently with little dependence on the direction of the incident sound wave.

There was, however, a significant difference between the sound fields at the middle frequencies (1000 and 2000

Hz). In assessing significant differences, it is perhaps more appropriate to compare the two alternative sound fields to the reverberant, three-speaker condition. At each of these frequencies, the semi-reverberant sound field resulted in greater attenuation than the reverberant, three-speaker sound field (at 1000 Hz, $\Delta = 1.61$ dB; at 2000 Hz, $\Delta = 1.73$ dB). Neither of these frequencies resulted in a significant difference between the reverberant, one-speaker and the reverberant, three-speaker sound field. These results are believed to be due to the diffraction characteristics of these middle frequencies, as discussed previously.

The high frequencies (6300 and 8000 Hz) also showed a significant effect. However, for these frequencies, the trend reversed. The reverberant, three-speaker sound field resulted in greater attenuation than the semi-reverberant sound field (at 6300 Hz, $\Delta = 1.84$ dB; at 8000 Hz, $\Delta = 2.51$ dB) and for 8000 Hz, it showed greater attenuation than the reverberant, one-speaker condition ($\Delta = 0.93$ dB). While no explanation is readily apparent, this shift in trend is in accordance with that found by Whittle and Robinson (1977), Berger (1985), and Bolka (1972), although Berger and Bolka did not report statistical significance.

Diffusivity - Significance and Interpretation of the Effects

Although the statistically significant differences among sound fields occured only for a limited number of frequencies and were small in magnitude, their existence cannot be ignored. They demonstrate that the sound field in which the hearing protectors are tested can have a significant effect on the attenuation measured for that device. The interpretation of statistical significance, however, depends upon the purpose for which the testing is being performed. This significance becomes an important point when the purpose of the measurement is for standards development, technically oriented research, product attenuation labeling, or other such critical applications. The criterion for a diffuse sound field should not be relaxed for these purposes.

However, because the dB differences among conditions were small (Δ maximum (max) = 4.25 dB at any frequency for any HPD; Δ max = 2 dB for the NRR) and limited in the number of frequencies and types of hearing protectors affected, they have modest practical significance. This suggests that the diffusivity criterion can be relaxed and these types of sound fields can be used in an industrial, on-site situation to obtain an estimate of the attenuation a particular worker is achieving with a particular device while on the job.

However, to obtain this estimate, it is important to note that this study applies to only those conditions in which all the other conditions specified by ANSI S3.19-1974 are met, including the ambient noise levels. If, in the field, the ambient noise levels are raised above that specified by ANSI S3.19-1974, it is quite possible that the unoccluded thresholds of the individuals would be raised to a greater extent than the occluded thresholds, thus resulting in a reduction in the attenuation measured for that device. Therefore, further study is necessary to determine if other requirements in the standard can also be relaxed. In addition, it is also important to note that the worst-case scenario in this experiment had lower sound absorption coefficients and higher reverberation times than the typical audiometric booth used in the industrial setting (E. Singer, personal communication, December 2, 1991), so it may be necessary to test a typical audiometric booth to determine if the above results apply.

It should be noted here that the majority of the significant differences found in this study were between the semi-reverberant (most degraded) and the reverberant, three-speaker (standardized) condition. Significant differences between the reverberant, one-speaker condition and the reverberant, three-speaker condition were limited to only one frequency and one hearing protector. This small, isolated difference tends to suggest that the limiting factor is the diffusivity of the sound field, not the number of sound sources, and that there is little difference between the two extreme sound-field diffusivity conditions, both of which fall within the tolerances of the ANSI S3.19-1974 standard.

The attenuation measured in these sound fields is compared to the manufacturer's attenuation data in Figures 33-36. In these figures, the means and standard deviations were based on the data before averaging across trials, as per EPA labeling requirements, whereas all other spectral attenuation figures in this document were based on the data after averaging across trials. At many frequencies the manufactures' data and the reverberant, three-speaker sound field data vary considerably. In fact, it is interesting to note that the differences among the three sound fields in this experiment are many times smaller than the differences between the reverberant, three-speaker sound field data and the manufactures' data. This would tend to suggest that interlaboratory differences between the same sound fields

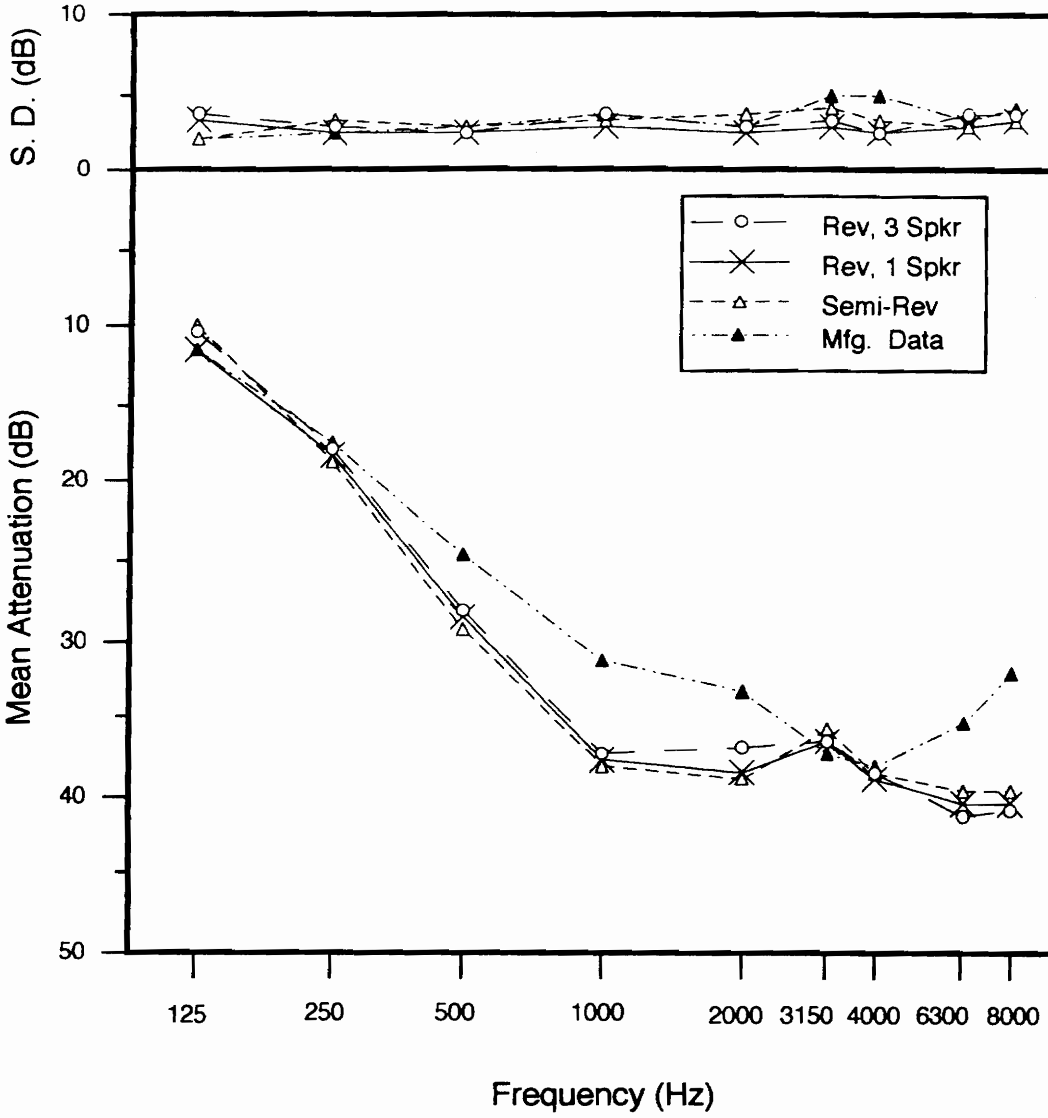


Figure 33. Spectral attenuation for the Cabot Safety Model 1720 earmuff, determined under the three sound field environments as compared to manufacturer's data.

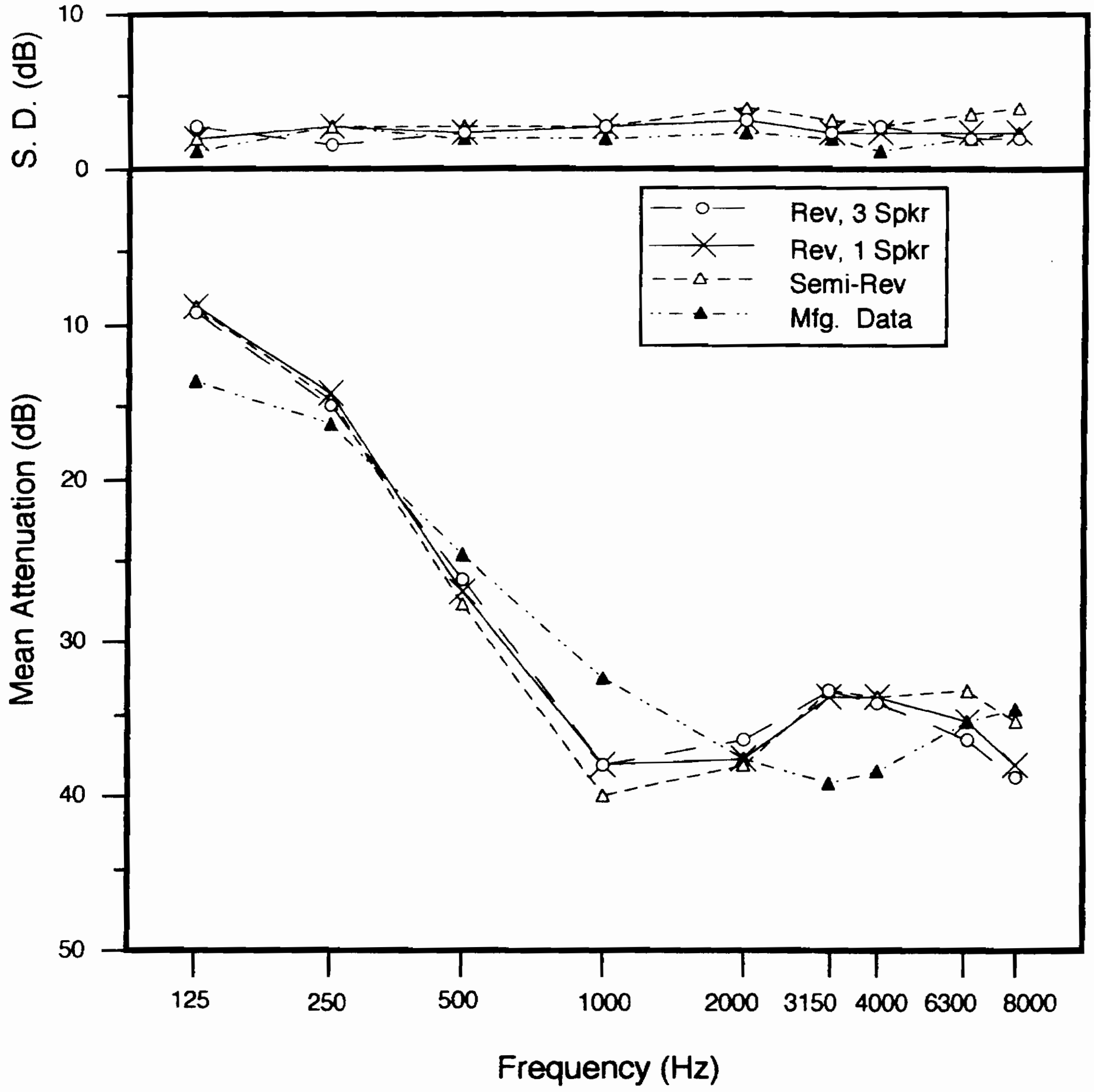


Figure 34. Spectral attenuation for the Peltor H9A earmuff, determined under the three sound field environments as compared to manufacturer's data.

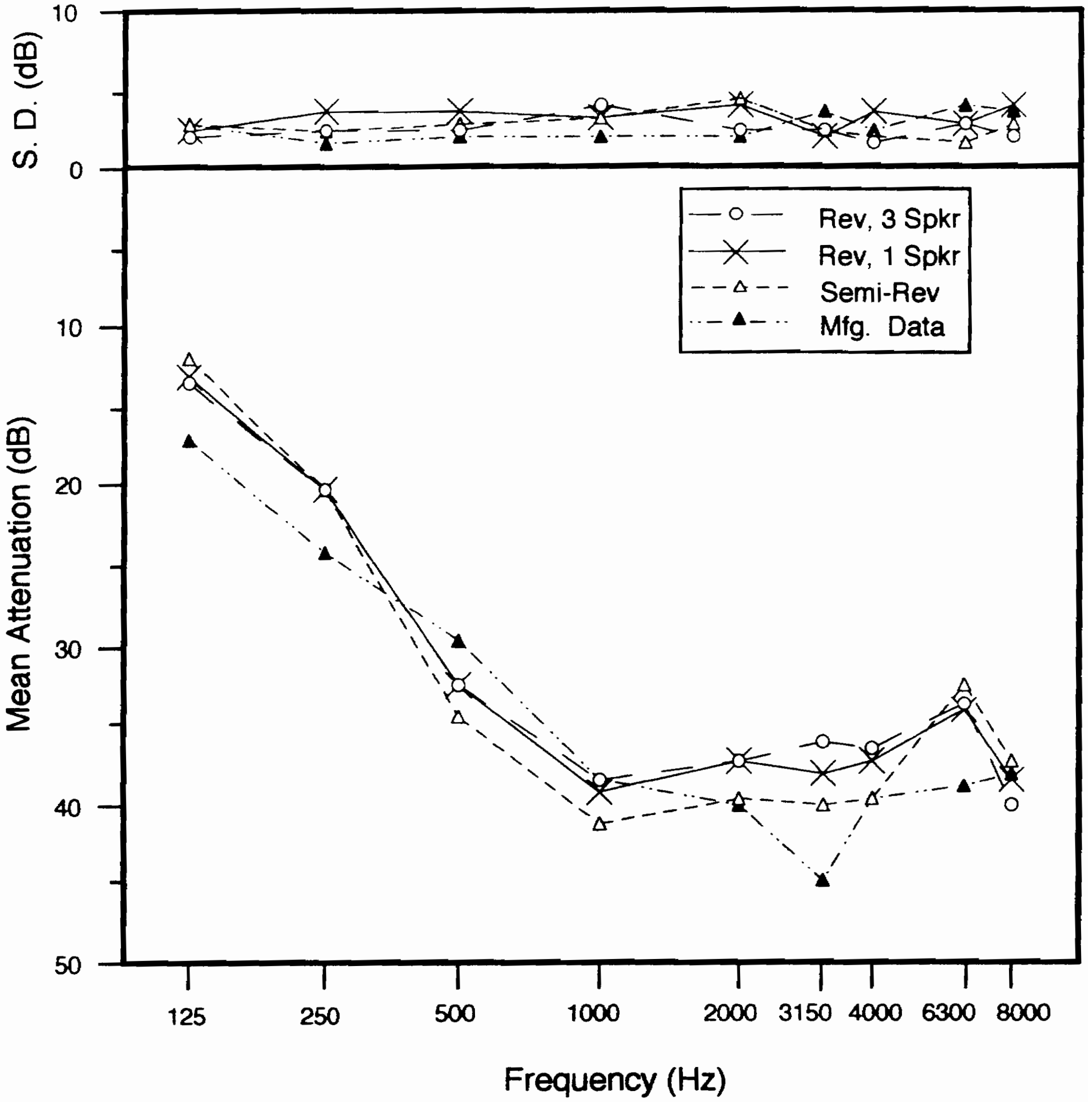


Figure 35. Spectral attenuation for the Peltor H7A earmuff, determined under the three sound field environments as compared to manufacturer's data.

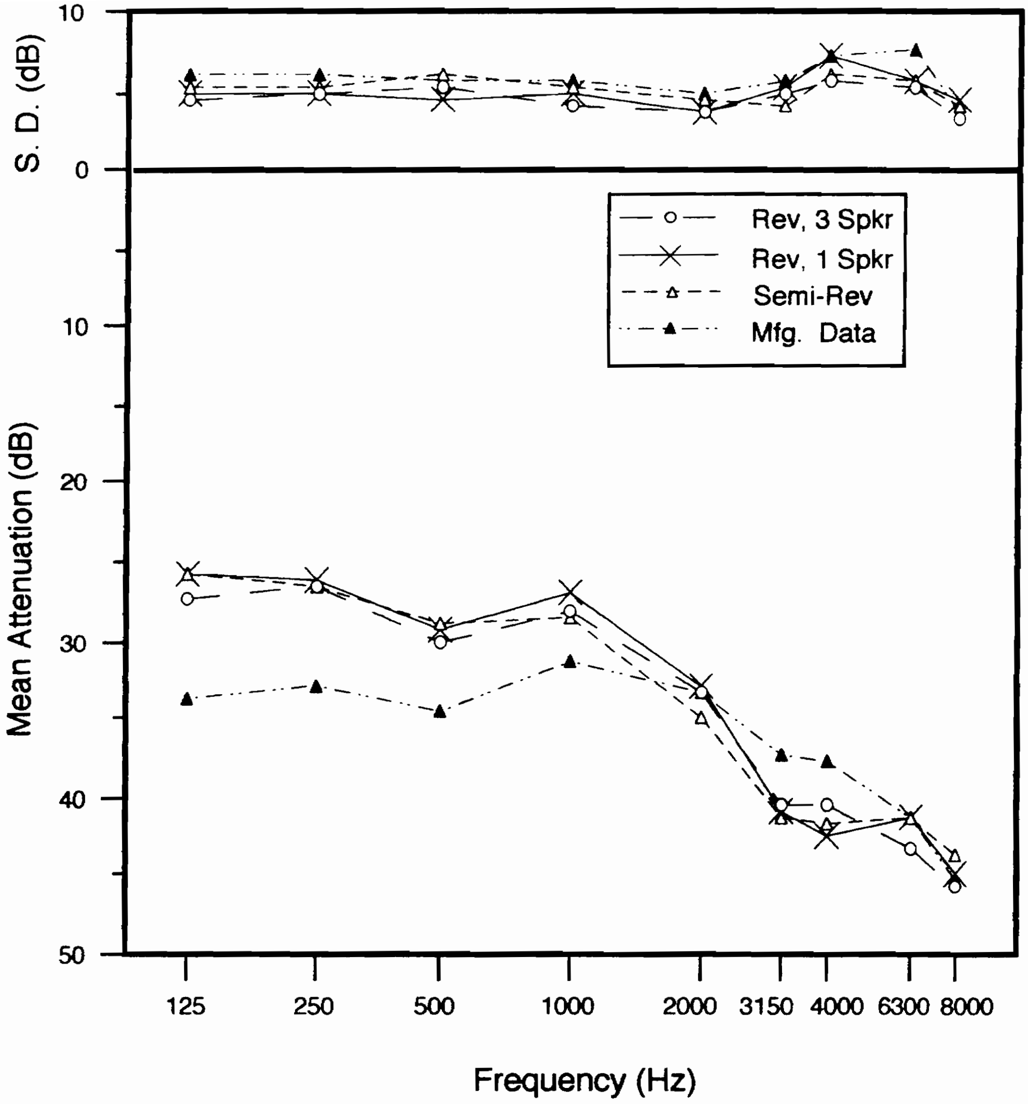


Figure 36. Spectral attenuation for the E-A-R UltraFit earplug, determined under the three sound field environments as compared to manufacturer's data.

are greater than intralaboratory differences between directional and diffuse sound fields.

Another interesting note is that there appears to be a systematic trend in how the data from this experiment differ from the manufacturers' data. In general, the manufacturers' data showed greater attenuation in the low frequencies (125, 250 Hz), less attenuation in the low-middle frequencies (500, 1000, 2000 Hz), greater attenuation in the high-middle frequencies (3150, 4000 Hz), and comparable attenuation in the high frequencies (6300, 8000 Hz). The appearance of a systematic trend suggests there may be an underlying cause for the differences shown here, although no one cause is readily apparent. These differences could be due to fitting technique, interpretation of the standard, subject experience, or sound field realization technique, among others.

Diffusivity Effects on the NRR_{PS}

The tested sound-field environments appeared to have little effect on the NRR_{PS} as discussed in the secondary ANOVA and post-hoc procedures. No interactions with or main effects of sound field were found. The only significant effect for this measure proved to be the main effect of hearing protector. This is of little surprise because it is common knowledge that hearing protectors differ in the attenuation they provide, due to a host of factors.

Diffusivity Effects on the NRR

Because the NRR is often considered the "bottom line" by the manufacturers and is the most important broadband attenuation measure for the purposes of determining OSHA compliance and comparing different HPDs, an NRR was calculated for each experimental condition. However, the NRR requires three trials from a minimum of 10 subjects and because this is exactly the number of subjects and trials taken at each experimental condition, only one NRR could be computed for each experimental condition and no hypothesis testing statistical procedures, such as ANOVA, could be performed on the data. Figures 37-40 show the results of these calculations, along with the manufacturer's NRR (obtained as per ANSI S3.19-1974 and published as of October, 1991) for comparison purposes. As can be seen in these figures, the maximum difference in the NRR among the sound-field conditions tested in this study was 2 dB, which only occurs once. More frequently, the difference was 1 or 0 dB. These graphs tend to suggest that the tested

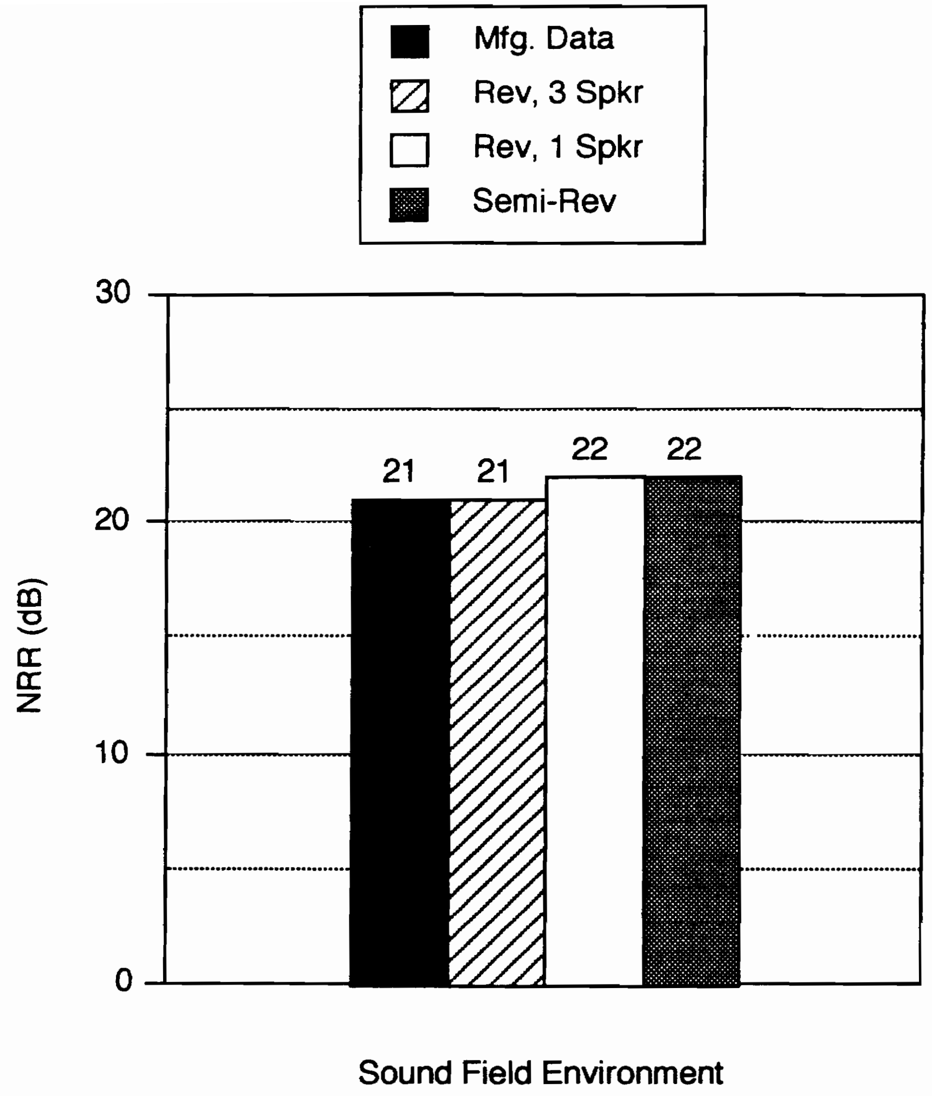


Figure 37. Noise Reduction Ratings (NRRs) for the Cabot Safety Model 1720 earmuff determined under the three sound-field environments as compared to manufacturer's NRR.

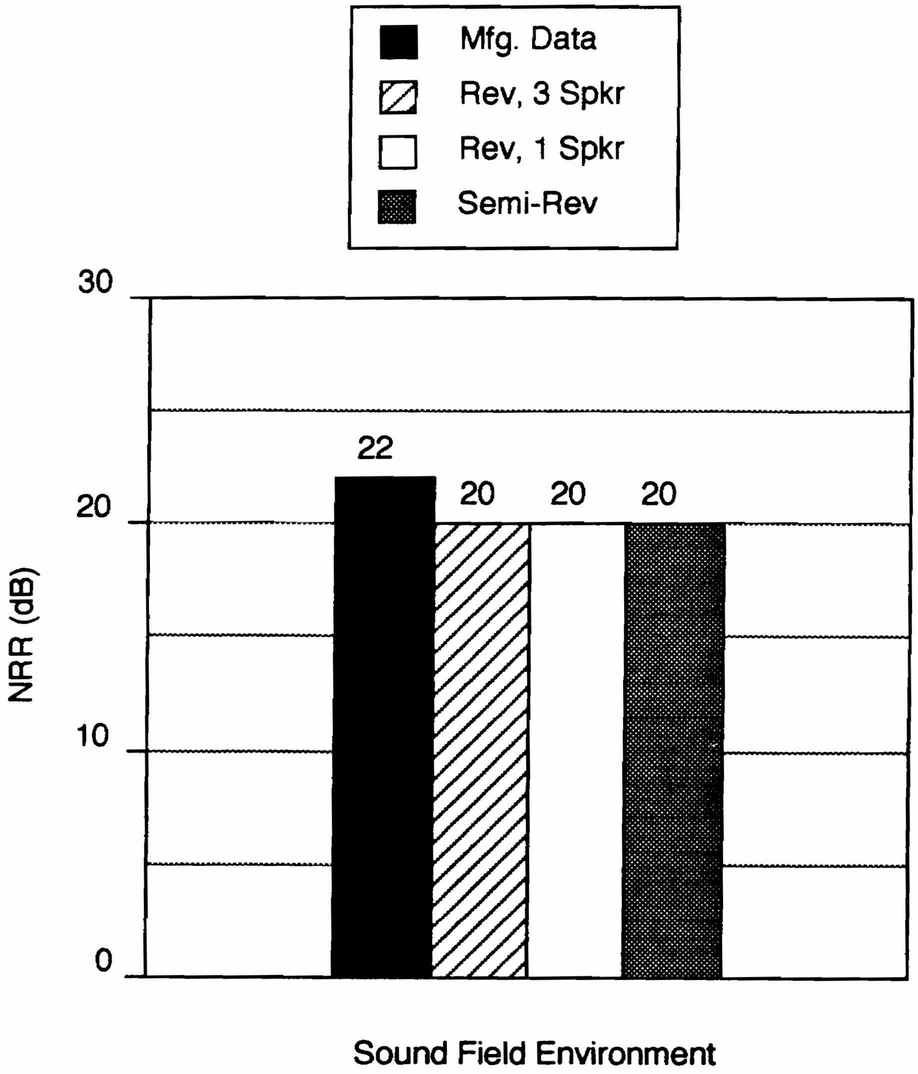


Figure 38. Noise Reduction Ratings (NRRs) for the Peltor H9A earmuff determined under the three sound field environments as compared to manufacturer's NRR.

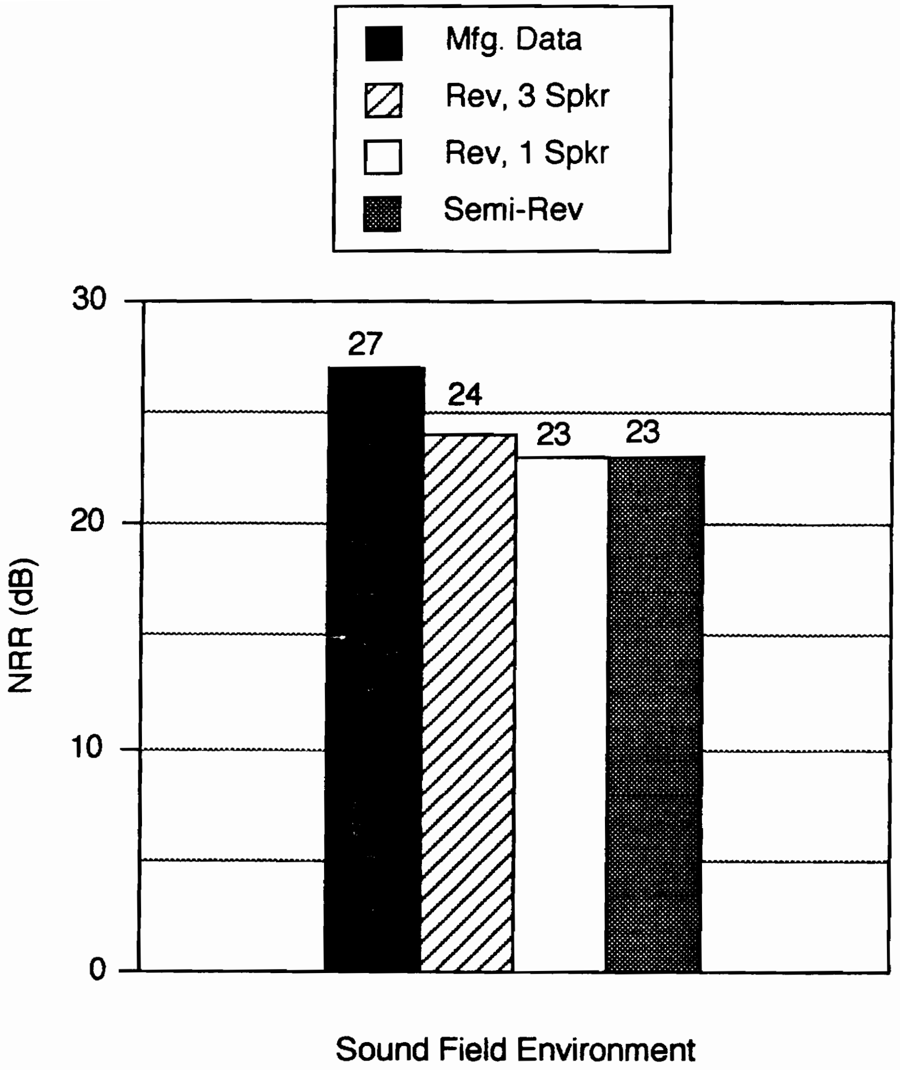


Figure 39. Noise Reduction Ratings (NRRs) for the Peltor H7A earmuff determined under the three sound field environments as compared to manufacturer's NRR.

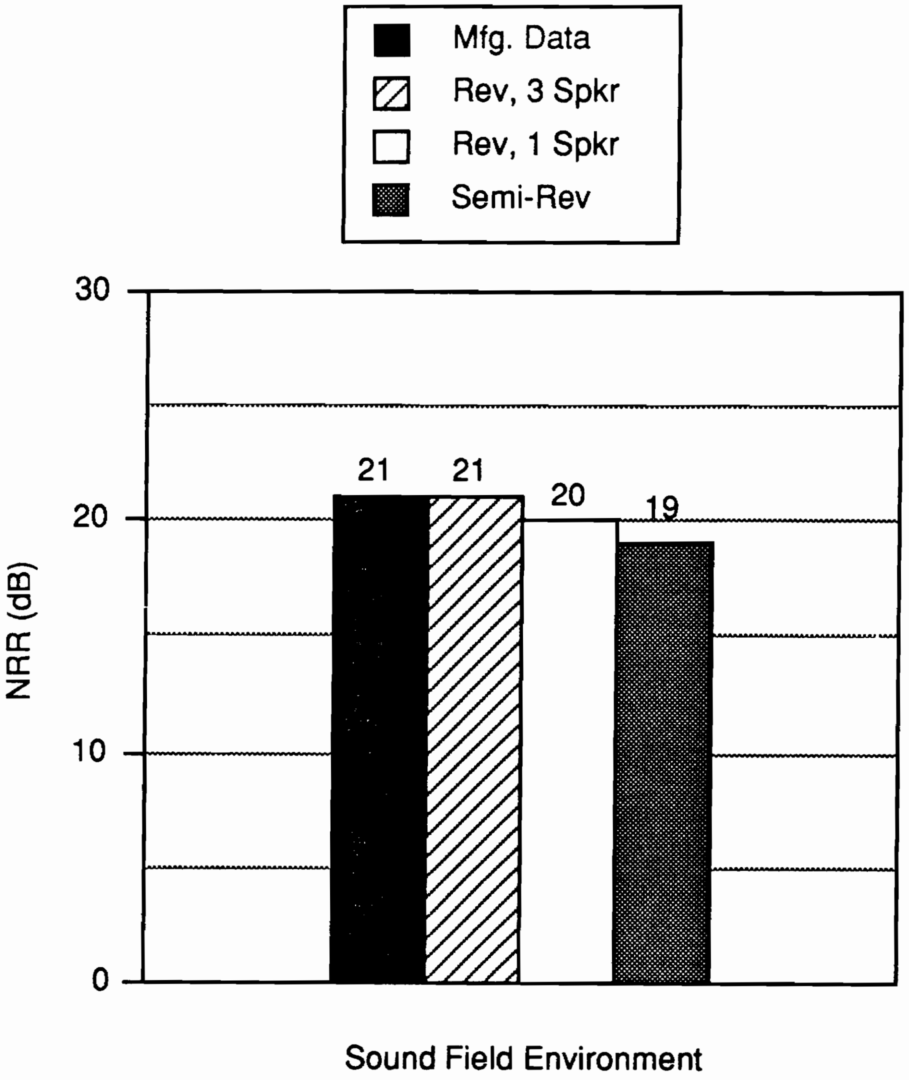


Figure 40. Noise Reduction Ratings (NRRs) for the E-A-R UltraFit earplug determined under the three sound-field environments as compared to manufacturer's NRR.

conditions have little effect on the overall NRR, for differences of this magnitude can often be attributed to normal test variation.

Another point should be made concerning these graphs. Often, the differences in the NRR within test conditions were less than the differences in the NRR between the experiment's reverberant, three-speaker condition (as per ANSI S3.19-1974) and the manufacturer's data (also as per ANSI S3.19-1974). The maximum difference between the manufacturer's data and the reverberant, three-speaker condition was +3 dB for the Peltor H7A, +2 dB for the Peltor H9A, 0 dB for the UltraFit, and 0 dB for the Cabot Safety Model 1720.

Hearing Protector-Specific Effects

The existence of the consistent HPD main effect in both the primary and secondary analyses warrants some attention. Normally, it would be possible only to point out this existence, but in this experiment, two of the hearing protectors (the Peltor H7A and the Peltor H9A earmuff) were as close to being identical as possible, except for the earcup volume. The Peltor H7A had a larger earcup volume (239.2 ml) than the Peltor H9A (172.0 ml) and resulted in significantly greater attenuation at most of the frequencies (125, 250, 500, 3150, 4000, and 8000 Hz) (Table 24). Only at 6300 Hz did the Peltor H9A have significantly greater attenuation. The Peltor H7A also resulted in significantly greater attenuation in the secondary analysis, for the NRR_{ps}, than the Peltor H9A.

These results tend to agree with that predicted by Berger (1986b), except that the attenuation of the small volume earmuff (Peltor H9A) did not exceed that of the larger volume earmuff (Peltor H7A) at the majority of the frequencies above 2000 Hz, as Berger suggested. This apparent relationship of earmuff volume to attenuation, coupled with the support of its trend in the literature (Berger, 1986b; Zwislocki, 1955; Zwislocki, 1957), suggests that earcup volume is one parameter that can be quantified and used in HPD design, although further study on a wide range of volumes is needed.

Frequency

The frequency main effect showed strong significance (Table 12). The results of the Newman-Keuls test show that, in general, attenuation tends to increases as frequency increases (Table 25). The strength of this effect is due, in part, to the fact that three earmuffs were tested and only one earplug. It is well-known that earmuffs do not provide as much attenuation in the low frequencies as they do in the high frequencies, and this trend is supported by the data collected in this experiment. The spectral attenuation of earplugs, on the other hand, tends to be more linear, generally providing more attenuation than earmuffs, on average, at low frequencies.

There are many concepts that can be used to explain why earmuffs do not attenuate low frequencies as well as high frequencies or as well as earplugs. One possible explanation is that earplugs have a better chance of sealing in the ear canal than earmuffs have of sealing around the entire pinna due in part to the effect of facial contour on the cushion seal. The result of a poor seal is the loss of attenuation in primarily the low frequencies. In addition, the earmuff has a much larger exposed surface area and is thus more likely to vibrate under the force of the low frequencies, whereas the high frequencies do not typically have as great a force. Furthermore, often the resonance frequency of the earcup shells is in the low frequencies, thus causing the earmuff to be even more susceptible to vibration (Zwislocki, 1955).

CONCLUSIONS

The conclusions that can be drawn from this experiment differ depending upon the intended application of the testing results. If the testing is to be used for critical applications such as technically oriented research, standards development, or product attenuation labeling, then the statistical differences shown in this experiment preclude comparisons to be made when the testing is performed in these different sound fields. For these purposes, the requirements of the test sound field should probably be strict and well-defined.

However, if the purpose of the testing is for determining how much attenuation a particular worker is receiving from a particular device, then the small differences reported in this study are not large enough to make a practical difference. In other words, the alternative sound fields explored in this study provide an excellent estimation of the attenuation actually achieved by that worker, although they cannot be directly compared to the manufacturer's data. These results are especially valuable to hearing conservation programs throughout industry, for they relax what is probably the most strict and difficult requirements (i.e., random-incidence sound field) of the American standards to meet in practice and thus should allow a number of these programs to verify the actual protection workers are receiving on the job. In addition, these results are applicable to many standards, internationally, several of which require such a random-incidence sound field to be obtained (ANSI S3.19-1974, ANSI S12.6-1984, BSI 5108:1983, CSA Z94.2-M1984, ISO 4869-1:1990, and SS 882151). However, these results were obtained when all other requirements of the ANSI standard were met and therefore apply only to those conditions. Other studies are necessary to determine if other requirements of the standard, such as the one-third octave bands of noise test signals, can be relaxed.

SUGGESTIONS FOR FUTURE RESEARCH

(1) Other aspects of the ANSI S3.19-1974 standard need further study to determine if they can or cannot be relaxed, such as the ambient noise level requirements and the one-third octave test band requirements.

(2) Studies need to be undertaken to determine if a diffuse field generated in a reverberant environment differs in attenuation measured from a diffuse field generated in an anechoic environment.

(3) An interlaboratory study is needed to find the source of the large interlaboratory differences reported herein and propose a solution to reduce this variability, possibly defining the protocol in the standards more clearly.

(4) There is also a need to determine how a typical audiometric test booth, with higher absorption interior surfaces and shorter reverberation times than the semi-reverberant environment tested herein, affects attenuation. This determination is necessary prior to setting up sound field test booths in the industrial setting for on-site verification of worker protection levels.

GLOSSARY

Anechoic room - a room in which the boundaries absorb nearly all the sound incident thereon, thereby affording effectively free field conditions (ANSI, 1973).

Center frequency (c.f.) - the geometric mean of the high and low band-edge frequencies (Ostergaard, 1986).

Diffuse sound field - a sound field of uniform energy density for which the directions of propagation at the position to be occupied by the subject are wholly random in distribution (ANSI, 1973).

Insertion loss - the decrease in sound power level measured at the location of the receiver when a sound barrier, sound attenuator, or other such element is inserted in the transmission path between the sound source and the receiver (Harris, 1991).

Noise reduction - the difference in sound pressure level between any two points along the path of sound propagation (Harris, 1991).

Open threshold of audibility - the minimum sound pressure level for a specified signal that is capable of evoking an auditory sensation when a hearing protector is not worn (ANSI, 1974).

Occluded threshold of audibility - the minimum sound pressure level for a specified signal that is capable of evoking an auditory sensation when the hearing protector under test is worn (ANSI, 1974).

Random-incidence response - the response averaged over all angles of incidence - all angles of incidence being equally probable from all directions at any given time or over a long period of time (Harris, 1991).

Real-ear attenuation at threshold - the mean value (in decibels) of the occluded threshold of audibility minus the open threshold of audibility for all listeners on all trials under otherwise identical test conditions (ANSI, 1974).

Reverberation - (1) the persistence of sound in an enclosed space, as a result of multiple reflections after the sound source has stopped; (2) the sound that persists in an enclosed space, as a result of repeated reflection or scattering, after the source of the sound has stopped (ANSI, 1973).

Reverberant room - a room having a long reverberation time, especially designed to make the sound field therein as diffuse as possible (ANSI, 1973).

Reverberation time, (T_{60}) - the time that would be required for the mean-square sound pressure level therein, originally in a steady state, to decrease 60 decibels after the source has stopped (ANSI, 1973).

REFERENCES

Abascus Concepts, SuperANOVA (1989). SuperANOVA: Accessible general linear modeling. Berkeley, CA: Abascus Concepts, Inc.

Abel, S. M., Alberti, P. W., Rokas, B. A. (1988). Gender differences in real-world hearing protector attenuation. Journal of Otolaryngology, 17(2), 86-92.

ANSI (1957). Method for the measurement of real-ear attenuation of ear protectors at threshold, ANSI Z24.22-1957. New York: American National Standards Institute.

ANSI (1973). Psychoacoustical terminology, ANSI S3.20-1973. New York: American National Standards Institute.

ANSI (1974). Method for the measurement of real-ear protection for hearing protectors and physical attenuation of earmuffs, ANSI S3.19-1974. New York: American National Standards Institute.

ANSI (1984). Method for the measurement of the real-ear attenuation of hearing protectors, ANSI S12.6-1984. New York: American National Standards Institute.

Békésy, G. (1947). A new audiometer. Acta Oto-laryngology, 35, 411-422.

Berger, E. H. (1979). EARLog #1 - The threshold shift method of measuring hearing protector attenuation. Journal of Sound and Vibration, 13(4), 12-13.

Berger, E. H. (1980). EARlog #5 - Hearing protector performance: How they work - and - what goes wrong in the real world. Sound and Vibration, 14(10), 14-17.

Berger, E. H. (1981). Re-examination of the low-frequency (500-1000 Hz) normal threshold of hearing in free and diffuse sound fields. Journal of the Acoustical Society of America, 70(6), 1635-1645.

Berger, E. H. (1982). Laboratory estimates of the real-world performance of hearing protectors. In P. W. Alberti (Ed.). Personal hearing protection in industry (pp. 299-314). New York: Raven Press.

Berger, E. H. (1983). Using the NRR to estimate the real world performance of hearing protector. Sound and Vibration, 17(1), 12-18.

Berger, E. H. (1985a). EARlog #16 - A new hearing protector standard - ANSI S12.6. American Industrial Hygiene Association Journal, 46(5), B26-B27.

Berger, E. H. (1985b). Is real-ear attenuation at threshold a function of hearing level? Journal of the Acoustical Society of America, 78(5), 1588-1595.

Berger, E. H. (1986a). Methods of measuring the attenuation of hearing protection devices. Journal of the Acoustical Society of America, 79(6), 1655-1687.

Berger, E. H. (1986b). Hearing protection devices. In E. H. Berger, W. D. Ward, J. C. Morrill, and L. H. Royster (Eds.), Noise and hearing conservation manual (4th ed.) (pp. 177-196). Akron, OH: American Industrial Hygiene Association.

Berger, E. H., and Kerivan, J. E. (1983). Influence of physiological noise and the occlusion effect on the measurement of real-ear attenuation at threshold. Journal of the Acoustical Society of America, 74(1), 81-94.

Berger, E. H., Royster, J. D., Casali, J. G., Merry, C. J., Mozo, B. T., and Royster, L. H. (1990). Results of a pilot interlaboratory comparison of REAT measurements of hearing protectors, coordinated by ANSI S12/WG11. Paper presented at the 120th Meeting of the Acoustical Society of America, San Diego, CA.

Bolka, D. F. (1972). Method of evaluating the noise and pure tone attenuation of hearing protectors. Unpublished doctoral dissertation, Pennsylvania State University, University Park, Pa.

Botsford, J. H. (1972). Ear protectors - their characteristics and uses. Sound and Vibration, 6(11), 24-29.

BSI (1983). Measurement of sound attenuation of hearing protectors, BS 5108:1983. London: British Standards Institute.

Casali, J. G. (1986). In defense of industrial workers' hearing. IE News (Ergonomics), 20(4), 1-6.

Casali, J. G. (1990). Listening closely to the noise of monster trucks. Roanoke Times and World News, March 5, p. A11.

Casali, J. G., and Epps, B. W. (1986). Effects of user insertion/donning instructions on noise attenuation of aural insert hearing protectors. Human Factors, 28(2). 195-210.

Casali, J. G., and Grenell, J. F. (1989). An exploratory study on moderate physical activity and selected design attribute effects on earmuff attenuation. Journal of the American Industrial Hygiene Association, 50(9). 480-485.

Casali, J. G., Lam, S. T., and Epps, B. W. (1986). _A post-hoc analysis of the gender effect in two studies on the achieved noise attenuation with earmuffs, earplugs, and canal caps_. Paper presented at the 1986 American Industrial Hygiene Conference, Dallas, TX.

Casali, J. G. and Mauney, D. W. (1990). _Custom-fitting earplug formed in-situ using foaming action_. Patent Application No. 569,812.

Casali, J. G. and Park, M.-Y. (1990). Attenuation performance of four hearing protectors under dynamic movement and different user fitting conditions. _Human Factors_, _32_(1), 9-25.

Casali, J. G. and Robinson, G. S. (1990). _A reverberant computer-controlled facility for hearing protection research and attenuation testing: verification re ANSI S3.19-1974_ (ISE Technical Report No. 9007; Audio Lab No. 12/1/90/5-HP). Blacksburg, VA: Virginia Polytechnic Institute and State University, Industrial and Systems Engineering Departement.

CSA (1984) _Hearing protectors, CSA Z94.2-M1984_. Ontario: Canadian Standards Association.

EPA (1981). Noise in America: the extent of the noise problem (EPA Report 550/9-81-101). Environmental Protection Agency, Washington, D.C.: U.S. Government Printing Office.

EPA (1990). Product noise labeling. Code of Federal Regulations, 40 Part 211, 120-137.

Dresser, W. (1975). Gunfire noise levels. The American Rifleman. 44-47.

Fisher, H. G., and Freedman, S. J. (1968). The role of the pinna in auditory localization. Journal of Auditory Research, 8, 15-26.

Gasaway, D. C. (1984). 'Sabotage' can wreck hearing conservation programs. National Safety News, 129(5), 56-60 and 66.

Greenhouse, S. W., and Geisser, S. (1959). On methods in the analysis of profile data. Psychometrika, 24(2), 95-112.

Harris, C. M. (1991). Handbook of acoustical measurements and noise control (3rd ed.). New York: McGraw-Hill, Inc.

Huynh, H., and Feldt, L. S. (1970). Conditions under which mean square ratios repeated measurements designs have exact F distributions. Journal of the American Statistical Association, 65(332), 1582-1589.

ISO (1961). Normal equal-loudness contours for pure-tones and normal threshold of hearing under free-field listening conditions, ISO R226-1861. Switzerland: International Organization for Standardization.

ISO (1975). As cited in Berger, E. H. (1981). Re-examination of the low-frequency (500-1000 Hz) normal threshold of hearing in free and diffuse sound fields. Journal of the Acoustical Society of America, 70(6), 1635-1645.

ISO (1990). Acoustics - hearing protectors - subjective method for the measurement of sound attenuation, Draft ISO 4869-1:1990(E). Switzerland: International Organization for Standardization.

Johnson, D. L. (1987). One rock concert = 2 1/2 year aging! Spectrum. 10-11.

Keppel, G. (1982). Design and analysis. Englewood Cliffs, NJ: Prentice-Hall

Killion, M. C. (1979). Equalization filter for eardrum-pressure recording using a KEMAR manikin. Journal of the Audio Engineering Society, 27(1/2), 13-16.

Kuhn, G. F. (1979). The pressure transformation from a diffuse sound field to the external ear and to the body and head surface. Journal of the Acoustical Society of America, 65(4), 991-1000.

Martin, A. M. (1977). The acoustic attenuation characteristics of 26 hearing protectors evaluated under the British standard procedure. Ann. Occup. Hyg., 20, 229-246.

Miller, R. (1978). Hearing protection: the state of the art. National Safety News, 117(3), 91-92.

Nixon, C. W. (1979). Hearing protective devices: ear protectors. In C. M. Harris (Ed.), Handbook of noise control (2nd ed.) (pp. 12-1 to 12-13). New York: McGraw-Hill.

Nixon, C. W. (1982). Hearing protection standards. In P. W. Alberti (Ed.), Personal hearing protection in industry (pp. 69-90). New York: Raven Press.

Ostergaard, P. B. (1986). Physics of sound. In E. H. Berger, W. D. Ward, J. C. Morrill, and L. H. Royster (Eds.), Noise and hearing conservation manual (4th ed.) (pp. 177-196). Akron, OH: American Industrial Hygiene Association.

Park, M.-Y. and Casali, J. G. (in press[a]). A controlled investigation of in-field attenuation performance of selected insert, circumaural, and canal cap hearing protectors. Human Factors.

Park, M.-Y. and Casali, J. G. (in press[b]). An empirical study of comfort afforded by various hearing protection devices: Laboratory versus field results. Applied Acoustics, in press.

Robinson, D. W., Whittle, L. S., and Bowsher, J. M. (1961). The loudness of diffuse sound fields. Acustica, 11, 397-404.

Roffler, S., and Butler, R. A. (1968). Factors that influence the localization of sound in the vertical plane. Journal of the Acoustical Society of America, 43, 1255-1259.

Rossing, T. D. (1990). The science of sound. Reading, Massachusetts: Addison-Wesley Publishing Co.

SAS Institute Inc. (1990). SAS/STAT user's guide, version 6 (4th ed.), Vol 1. Cary, N. C.: SAS Institute Inc.

Shaw, E. A. G. (1974). Transformation of sound pressure level from the free field to the eardrum in the horizontal plane. Journal of the Acoustical Society of America, 56(6), 1848-1861.

Shipley, L. B. (1985). Hearing loss comp becoming today's major industry issue. National Safety and Health News, 35-38.

SS (1981). Hearing protectors test methods, SS 882151. Sweden: SIS Swedish Standardisation Commission.

Wallach, H. (1940). The roll of head movements and vestibular and visual cues in sound localization. Journal of Experimental Psychology, 27, 339-368.

Ward, W. D. (1976). Transient changes in hearing. In G. Rossi and M. Vigone (Eds.). Man and noise. Milan: Edizioni Minerva Medica.

Ward, W. D. (1986). Anatomy and physiology of the ear: normal and damaged hearing. In E. H. Berger, W. D. Ward, J. C., Morrill, and L. H. Royster (Eds.), Noise and hearing conservation manual (4th ed.) (pp. 177-196). Akron, OH: American Industrial Hygiene Association.

Waugh, R. (1974). Pure-tone, third-octave, and octave-band attenuation of ear protectors. Journal of the Acoustical Society of America, 56(6), 1866-1869.

Webster, J. C., Thompson, P. O., and Beitscher, H. R. (1956). Noise bands versus pure tones as stimuli in measuring the acoustic attenuation of ear protective devices. Journal of the Acoustical Society of America, 28(4), 631-638.

Whittle, L. S., and Robinson, D. W. (1977). On the measurement of real-ear attenuation of hearing protectors by standardised test methods. National Physical Laboratory Acoustics Report Ac79.

Wiener, F. M. and Ross, D. A. (1946). The pressure distribution in the auditory canal in a progressive sound field. _Journal of the Acoustical Society of America_, _18_, 401-408.

Zwislocki, J. (1955). Sound attenuation by earphone sockets. _Journal of the Acoustical Society of America_, _27_, 146-158.

Zwislocki, J. (1957). Ear protectors. In C. M. Harris (Ed.), _Handbook of noise control_ (pp 8.1-8.27). New York: McGraw-Hill, Inc.

APPENDIX A

Sound-Field Directionality Data

Sound-Field Directionality Data for Microphone Rotation About the X-Axis for the Reverberant, Three Speaker Sound-Field Environment (Data are in dB) (Adapted from Casali and Robinson, 1990)

Mic Pos.	1/3 OB center (Hz)								
	125	250	500	1000	2000	3150	4000	6300	8000
0	51.6	62.3	62.1	62.1	59.3	58.1	59.5	57.5	56.5
15	50.5	61.7	62.0	62.0	59.5	58.0	59.5	57.5	56.5
30	48.2	61.9	62.1	61.8	59.5	58.0	59.4	57.3	56.4
45	47.8	62.0	62.3	61.6	59.5	58.1	59.5	57.1	56.3
60	48.6	62.2	62.1	61.6	59.4	58.2	59.7	56.9	56.4
75	47.6	61.3	62.5	61.8	59.2	58.4	59.8	56.9	56.6
90	48.5	62.3	62.5	61.8	59.2	58.4	59.8	56.8	56.7
105	48.6	61.9	62.5	61.9	59.1	58.5	59.9	56.9	57.0
120	49.0	61.6	62.5	61.9	59.0	58.4	59.9	57.1	57.2
135	50.0	61.9	62.4	62.1	59.0	58.3	59.8	57.2	57.2
150	50.3	62.3	62.5	62.3	59.2	58.2	59.8	57.4	57.3
165	50.8	62.0	62.6	61.9	59.2	58.1	59.5	57.4	57.1
180	50.7	62.1	62.1	61.9	59.3	58.0	59.4	57.3	56.8
195	50.8	62.0	62.1	61.9	59.5	58.1	59.3	57.4	56.6
210	50.2	62.4	61.9	61.7	59.4	57.9	59.3	57.3	56.4
225	50.2	62.3	61.9	61.6	59.5	57.9	59.4	57.1	56.2
240	49.8	61.9	61.9	61.6	59.5	58.2	59.5	56.9	56.3
255	50.9	62.0	62.2	61.8	59.5	58.3	59.6	56.9	56.4
270	50.0	62.0	62.3	61.7	59.4	58.4	59.8	56.9	56.7
285	49.3	62.1	62.1	61.9	59.1	58.5	60.0	56.9	57.0
300	48.3	61.8	62.4	62.0	59.1	58.5	59.9	57.0	57.0
315	47.1	61.6	62.2	62.1	58.9	58.3	59.9	57.1	56.9
330	48.4	61.9	62.2	62.2	59.1	58.3	59.8	57.3	56.7
345	51.6	61.9	62.8	62.2	59.1	58.2	59.7	57.3	56.4
Mean (X)	49.5	62.0	62.3	61.9	59.3	58.2	59.7	57.1	56.7

Sound-Field Directionality Data for Microphone Rotation About the Y-Axis for the Reverberant, Three Speaker Sound-Field Environment (Data are in dB) (Adapted from Casali and Robinson, 1990)

Mic	1/3 OB center (Hz)								
Pos.	125	250	500	1000	2000	3150	4000	6300	8000
0	49.5	61.7	62.4	62.1	59.2	57.7	59.3	57.1	56.2
15	47.6	62.0	61.8	62.0	59.2	57.9	59.6	57.1	56.2
30	47.1	62.3	61.7	61.9	59.1	58.2	59.8	57.0	56.2
45	48.4	61.8	61.9	61.9	58.6	58.5	60.0	57.0	56.4
60	49.9	61.4	62.2	61.9	58.4	58.6	60.1	56.9	56.4
75	50.8	60.3	62.9	62.0	58.0	58.7	60.1	56.8	56.3
90	51.9	59.9	63.0	62.0	58.0	58.7	59.9	56.8	56.2
105	51.9	59.3	63.6	61.9	58.1	58.3	59.7	56.9	56.1
120	52.2	60.2	63.4	61.9	58.4	58.1	59.5	56.7	56.0
135	51.5	60.6	63.2	61.9	58.7	57.9	59.2	56.8	56.0
150	51.0	61.0	63.0	61.9	59.0	57.8	59.1	57.0	56.0
165	49.5	61.7	62.7	61.7	59.2	57.7	59.1	57.1	56.2
180	48.3	62.2	62.2	61.8	59.3	57.5	59.2	57.0	56.2
195	46.6	62.5	61.7	62.0	59.1	57.7	59.4	57.0	56.3
210	45.9	62.2	61.7	61.9	58.9	57.9	59.5	57.0	56.4
225	47.5	62.4	61.8	61.9	58.6	58.1	59.8	56.8	56.4
240	49.0	61.5	62.1	61.9	58.3	58.3	59.8	56.7	56.4
255	50.7	60.9	62.4	61.7	58.0	58.4	59.9	56.7	56.2
270	51.2	60.9	63.0	61.8	58.0	58.3	59.8	56.8	56.1
285	52.2	60.2	63.3	61.8	58.0	58.2	59.6	56.8	56.0
300	52.0	59.5	63.1	61.8	58.2	58.0	59.5	56.8	55.9
315	52.0	60.4	63.2	61.9	58.5	57.9	59.2	56.8	55.9
330	51.3	60.5	62.9	61.9	58.8	57.6	59.0	56.7	55.9
345	50.7	61.4	62.6	61.9	58.9	57.5	59.0	56.8	56.0
Mean (Y)	49.9	61.1	62.6	61.9	58.6	58.1	59.5	56.9	56.2

Sound-Field Directionality Data for Microphone Rotation About the Z-Axis for the Reverberant, Three Speaker Sound-Field Environment (Data are in dB) (Adapted from Casali and Robinson, 1990)

Mic Pos.	1/3 OB center (Hz)								
	125	250	500	1000	2000	3150	4000	6300	8000
0	45.5	62.2	62.2	61.6	58.7	58.3	59.9	56.8	56.8
15	45.5	62.2	62.5	61.7	58.8	58.2	60.0	56.9	57.1
30	47.2	61.9	62.9	62.0	58.7	58.0	60.2	56.9	57.1
45	48.6	61.7	63.1	62.1	58.5	58.0	60.2	57.0	57.1
60	50.2	61.8	63.0	62.1	58.1	58.0	60.0	56.9	56.8
75	50.9	60.8	63.1	61.9	58.0	58.1	59.9	56.9	56.5
90	51.7	60.1	62.8	61.7	57.8	58.2	59.6	56.8	56.2
105	51.7	59.7	62.8	61.5	58.1	58.4	59.4	56.7	56.1
120	50.9	60.1	62.6	61.1	58.2	58.4	59.4	56.8	56.2
135	50.3	60.4	62.2	61.2	58.7	58.4	59.5	56.8	56.4
150	49.7	61.4	61.9	61.3	58.8	58.5	59.6	56.8	56.5
165	48.5	61.5	61.9	61.4	58.9	58.4	59.7	56.7	56.6
180	48.2	61.7	62.2	61.8	58.8	58.3	60.0	56.9	56.8
195	47.8	62.0	62.5	62.0	58.8	58.3	60.1	57.0	57.0
210	48.7	62.1	63.0	62.2	58.7	58.2	60.3	57.1	57.2
225	49.9	61.1	63.2	62.4	58.5	58.0	60.2	57.2	57.1
240	50.9	61.1	63.4	62.4	58.2	58.1	60.1	57.0	56.8
255	51.1	60.1	63.1	62.1	58.1	58.1	59.7	56.8	56.4
270	51.5	59.8	62.8	62.1	57.9	58.0	59.5	56.7	56.2
285	51.8	58.8	62.9	62.0	58.0	58.1	59.3	56.5	56.1
300	51.2	59.8	62.8	61.6	58.1	58.1	59.1	56.5	56.0
315	50.1	60.5	62.4	61.4	58.3	58.3	59.2	56.6	56.4
330	49.4	61.1	62.3	61.2	58.6	58.4	59.5	56.7	56.5
345	47.1	61.9	62.2	61.3	58.8	58.3	59.7	56.9	56.7
Mean (Z)	49.5	61.0	62.7	61.8	58.4	58.2	59.8	56.8	56.6

Sound-Field Directionality Data for Microphone Rotation About the X-Axis for the Reverberant, One Speaker Sound-Field Environment (Data are in dB)

Mic Pos.	1/3 OB center (Hz)								
	125	250	500	1000	2000	3150	4000	6300	8000
0	44.4	59.1	59.9	59.6	56.2	56.0	57.0	55.0	55.2
15	44.1	60.4	60.3	59.8	56.4	55.5	56.9	55.0	55.0
30	43.4	60.2	59.3	60.0	56.9	55.7	57.3	55.4	55.2
45	42.9	60.4	58.7	59.9	57.3	56.0	57.7	55.9	55.5
60	43.4	60.6	58.5	60.4	58.1	56.7	58.2	56.4	56.0
75	43.9	60.6	57.5	60.6	58.3	57.2	58.6	56.9	56.4
90	44.3	59.4	58.0	60.9	58.4	57.7	58.9	57.2	56.8
105	45.8	59.1	57.7	60.9	58.4	57.9	59.0	57.4	56.8
120	46.3	58.7	58.7	60.6	58.3	57.6	58.8	57.0	56.8
135	45.6	58.8	59.3	60.6	57.5	57.3	58.3	56.5	56.7
150	45.7	59.3	59.9	59.9	57.1	57.1	58.0	55.8	56.2
165	45.8	59.4	59.8	59.5	56.5	56.7	57.4	55.1	55.6
180	46.2	60.4	59.9	59.5	56.4	56.2	57.1	54.6	55.1
195	45.6	60.7	59.5	59.8	56.5	56.2	57.0	54.8	54.9
210	44.5	61.1	59.2	59.9	56.9	56.2	57.3	55.3	55.1
225	43.2	61.5	58.7	60.2	57.6	56.7	57.9	56.0	55.6
240	42.3	61.3	58.3	60.3	58.0	57.1	58.6	56.7	56.3
255	42.6	60.7	58.0	60.7	58.4	57.7	58.9	57.2	56.8
270	42.7	60.5	57.8	60.8	58.6	57.9	59.1	57.5	57.4
285	43.1	59.3	58.2	60.6	58.6	58.1	59.1	57.4	57.3
300	43.8	58.8	58.7	60.7	58.0	58.0	59.0	57.2	57.1
315	43.8	59.1	59.4	60.6	57.5	57.5	58.4	56.6	56.7
330	43.6	59.0	60.0	60.0	56.8	57.1	57.8	55.9	56.2
345	43.8	59.5	59.9	59.9	56.3	56.3	57.2	55.3	55.6
Mean (X)	44.2	59.9	59.0	60.2	57.5	56.9	58.1	56.2	56.1

Sound-Field Directionality Data for Microphone Rotation About the Y-Axis for the Reverberant, One Speaker Sound-Field Environment (Data are in dB)

Mic	1/3 OB center (Hz)								
Pos.	125	250	500	1000	2000	3150	4000	6300	8000
0	44.6	59.5	60.3	59.5	56.2	55.2	57.1	54.9	54.7
15	42.7	60.0	60.3	59.7	56.1	55.2	57.4	54.7	54.7
30	42.4	60.1	60.2	59.6	56.1	55.0	57.8	54.9	54.6
45	43.5	59.8	61.5	59.5	56.2	55.4	58.1	55.1	54.8
60	45.4	58.7	62.4	59.3	56.3	55.9	58.6	55.6	54.8
75	47.7	56.7	63.1	58.8	56.5	56.4	58.6	55.9	55.0
90	48.0	55.2	63.8	58.4	56.4	56.9	58.6	56.0	54.9
105	48.9	55.5	63.6	58.3	56.4	57.1	58.4	56.2	55.0
120	49.2	55.6	63.3	58.2	56.1	56.9	58.1	56.3	54.9
135	48.9	57.3	63.0	58.5	56.3	56.7	57.9	56.0	55.0
150	48.8	58.1	62.1	58.9	56.1	56.4	57.5	55.9	54.9
165	48.0	59.8	61.0	59.2	56.3	55.9	57.2	55.3	54.9
180	45.9	60.2	59.9	59.6	56.1	55.5	57.2	55.0	54.8
195	44.2	60.9	59.5	59.7	56.4	55.4	57.5	54.8	54.8
210	43.7	60.5	59.9	59.7	56.5	55.6	57.8	54.8	54.7
225	43.3	60.3	60.9	59.4	56.5	55.9	58.3	55.1	54.8
240	45.1	58.6	62.2	59.0	56.6	56.5	58.7	55.6	54.8
255	46.6	57.5	62.9	58.5	56.4	56.7	58.9	56.0	55.0
270	48.0	55.9	63.4	58.1	56.5	57.1	58.9	56.3	55.1
285	48.9	55.4	63.5	57.9	56.3	57.1	58.7	56.4	55.2
300	48.7	55.2	63.4	58.2	56.4	57.0	58.2	56.4	55.3
315	48.7	56.8	62.8	58.5	56.3	56.7	57.8	56.1	55.2
330	48.1	58.2	61.7	59.1	56.2	56.3	57.4	55.5	55.1
345	46.4	58.9	60.9	59.3	56.2	55.8	57.1	55.2	54.9
Mean (Y)	46.5	58.1	61.9	59.0	56.3	56.2	58.0	55.6	54.9

Sound-Field Directionality Data for Microphone Rotation About the Z-Axis for the Reverberant, One Speaker Sound-Field Environment (Data are in dB)

Mic Pos.	1/3 OB center (Hz)								
	125	250	500	1000	2000	3150	4000	6300	8000
0	44.6	59.3	57.5	60.5	58.1	57.4	59.5	56.9	57.4
15	44.6	59.2	58.3	60.4	57.7	56.8	59.3	56.4	56.9
30	44.7	57.8	60.1	60.2	57.1	56.3	59.1	56.0	56.3
45	45.5	57.0	61.8	59.9	56.6	56.0	58.8	55.8	55.5
60	47.3	55.3	62.9	59.5	56.3	56.0	58.6	55.7	54.7
75	48.1	54.9	63.4	59.1	56.4	56.2	58.4	55.7	54.2
90	48.5	56.5	63.5	58.6	56.7	56.8	58.4	55.9	54.3
105	48.4	57.2	63.4	58.4	57.3	57.5	58.6	56.1	55.1
120	48.1	59.1	62.2	58.7	58.0	57.9	59.0	56.5	56.3
135	47.8	59.7	60.9	59.5	58.5	58.0	59.6	57.0	57.3
150	46.0	60.4	59.5	60.1	58.7	58.0	59.8	57.1	57.6
165	44.4	60.7	57.8	60.5	58.8	57.8	59.8	57.0	57.6
180	42.2	60.3	57.9	60.9	58.3	57.3	59.7	56.8	57.4
195	41.4	59.9	59.0	60.8	57.7	56.8	59.6	56.6	57.1
210	43.0	58.4	60.7	60.4	57.2	56.5	59.3	56.3	56.5
225	45.1	56.9	62.4	60.0	56.6	56.2	58.7	55.9	55.5
240	46.1	55.6	63.0	59.5	56.2	56.2	58.5	55.6	54.7
255	47.2	54.4	63.5	58.7	56.3	56.5	58.2	55.7	53.9
270	48.0	55.5	63.7	58.4	56.6	56.9	58.3	55.9	54.1
285	48.5	56.5	63.3	58.4	57.3	57.3	58.5	56.2	54.9
300	48.2	58.1	62.8	58.6	57.9	57.8	58.8	56.6	56.0
315	47.5	59.1	61.5	59.4	58.2	58.0	59.2	57.1	57.0
330	46.5	59.6	59.7	59.7	58.6	57.9	59.5	57.2	57.5
345	45.1	66.0	58.0	60.3	58.3	57.8	59.7	57.1	57.6
Mean (Z)	46.1	58.0	61.1	59.6	57.5	57.1	59.0	56.4	56.1

Sound-Field Directionality Data for Microphone Rotation About the X-Axis for the Semi-Reverberant Sound-Field Environment (Data are in dB)

Mic Pos.	1/3 OB Center (Hz)								
	125	250	500	1000	2000	3150	4000	6300	8000
0	37.2	56.6	62.4	59.5	55.4	55.2	56.7	53.8	53.9
15	39.1	56.8	62.2	59.1	54.1	54.7	56.5	53.8	53.3
30	40.0	57.2	61.8	59.2	53.5	54.7	56.3	54.4	53.6
45	40.5	58.2	61.7	59.8	54.6	55.2	56.5	55.7	54.8
60	41.3	59.2	61.7	60.1	56.5	56.1	57.0	57.1	56.8
75	41.4	59.1	62.0	60.6	57.8	56.9	57.4	58.3	58.3
90	41.6	59.6	62.3	60.8	58.7	57.7	57.9	59.1	59.2
105	40.9	59.6	62.8	60.7	59.3	57.9	58.1	59.1	59.3
120	39.4	59.1	62.3	60.7	59.3	57.8	58.0	58.5	58.7
135	39.3	58.3	62.4	60.3	58.8	57.4	57.8	57.5	57.7
150	38.3	58.1	62.4	59.9	58.1	56.9	57.5	56.7	56.9
165	39.4	57.2	62.0	59.5	56.9	56.3	57.1	55.3	55.5
180	41.7	57.4	61.5	59.0	55.2	55.2	56.8	54.4	54.6
195	42.4	57.7	61.3	58.9	53.9	54.6	56.5	54.3	53.7
210	43.4	59.0	61.1	59.3	54.2	54.7	56.6	55.0	53.8
225	44.4	59.5	61.4	60.0	55.7	55.6	56.7	56.1	55.1
240	44.7	60.3	61.9	60.7	57.5	56.5	57.1	57.5	57.1
255	45.1	60.7	62.2	61.0	58.9	57.6	57.5	58.7	58.8
270	43.9	61.0	62.6	61.5	59.8	58.3	58.0	59.5	59.7
285	42.9	60.7	63.0	61.2	60.4	58.5	58.2	59.6	59.8
300	41.9	59.9	62.9	61.2	60.3	58.4	58.3	59.0	59.1
315	40.5	59.5	62.9	60.8	60.0	57.8	58.1	57.9	57.9
330	38.3	58.1	63.1	60.3	58.9	56.9	57.8	56.3	56.3
345	36.7	57.7	62.4	59.7	57.5	55.9	57.4	54.8	54.8
Mean (X)	41.0	58.8	62.2	60.2	57.3	56.5	57.3	56.8	56.6

Sound-Field Directionality Data for Microphone Rotation About the Y-Axis for the Semi-Reverberant Sound-Field Environment (Data are in dB)

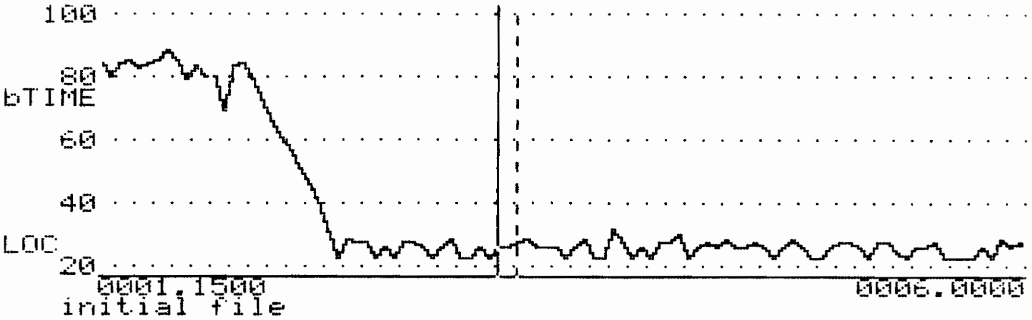
Mic	1/3 OB center (Hz)								
Pos.	125	250	500	1000	2000	3150	4000	6300	8000
0	36.6	56.9	62.1	59.4	54.8	55.0	56.6	54.2	54.8
15	36.6	56.9	62.0	59.7	54.6	55.0	56.5	54.3	54.6
30	36.1	56.7	61.8	59.1	53.9	54.4	56.3	53.9	54.0
45	36.2	55.0	60.8	58.3	52.6	53.2	55.4	53.5	53.1
60	37.0	52.4	59.5	56.7	51.0	51.9	54.5	53.2	52.5
75	36.5	48.8	57.0	54.3	48.8	50.1	53.4	52.7	51.9
90	37.6	44.5	54.5	51.6	47.7	49.4	52.7	52.4	51.6
105	38.1	46.3	53.5	50.8	48.1	49.8	52.6	52.4	52.0
120	39.3	51.0	55.1	52.7	49.9	51.5	53.1	52.5	52.5
135	40.0	53.5	56.9	54.8	51.5	52.4	53.8	52.4	52.5
150	40.0	55.1	58.7	56.4	52.7	53.6	54.8	52.8	53.1
165	40.0	56.8	60.3	57.5	53.4	54.3	55.6	53.4	53.8
180	41.4	57.5	61.2	58.7	54.0	54.8	56.4	54.0	54.1
195	40.9	57.4	61.6	59.0	53.7	54.7	56.5	54.3	54.0
210	39.8	57.2	60.8	58.5	53.0	54.2	56.2	54.4	53.7
225	39.5	55.9	60.1	57.7	51.9	53.1	55.5	54.1	53.1
240	38.7	54.0	58.5	56.1	50.2	52.0	54.5	53.6	52.3
255	37.6	51.2	56.3	54.0	48.3	50.3	53.6	52.9	50.9
270	35.9	46.6	53.0	51.6	47.8	49.2	53.0	52.0	49.7
285	35.5	46.1	53.2	51.4	49.3	49.8	53.4	51.4	49.7
300	34.5	49.5	56.0	53.3	51.2	51.1	54.1	51.7	50.7
315	34.4	53.0	58.8	55.7	52.8	52.6	55.1	52.1	52.1
330	35.3	55.4	60.8	57.6	54.4	54.1	55.9	53.1	53.2
345	36.2	56.8	61.8	58.7	54.7	54.7	56.4	53.8	53.9
Mean (Y)	37.7	53.1	58.5	56.0	51.7	52.6	54.8	53.1	52.7

Sound-Field Directionality Data for Microphone Rotation About the Z-Axis for the Semi-Reverberant Sound-Field Environment (Data are in dB)

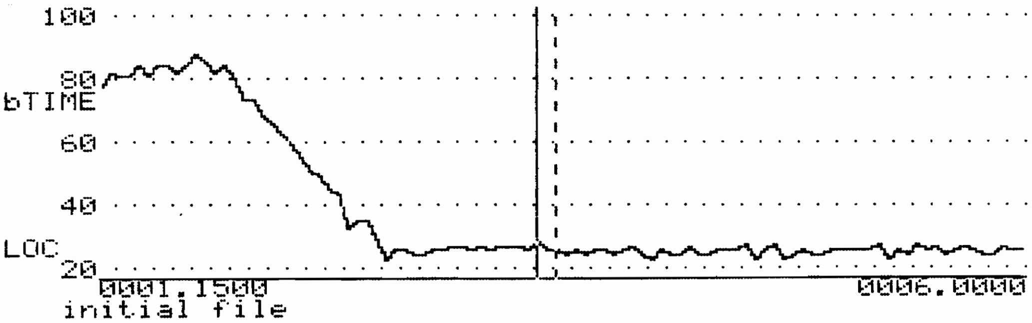
Mic Pos.	1/3 OB center (Hz)								
	125	250	500	1000	2000	3150	4000	6300	8000
0	40.5	59.7	62.4	61.0	59.4	56.9	57.7	58.6	59.6
15	40.1	59.3	62.2	60.4	59.2	56.7	57.5	58.1	59.1
30	39.3	58.6	61.6	59.3	58.4	56.1	57.1	57.5	58.2
45	38.4	56.7	60.2	57.4	56.7	54.7	56.3	56.5	56.8
60	36.8	53.4	57.5	53.9	53.3	52.9	55.2	55.9	55.2
75	36.5	48.7	55.0	50.0	49.1	51.2	54.1	55.2	54.4
90	37.1	46.0	53.4	50.6	47.7	51.4	54.0	55.2	53.9
105	39.1	51.4	55.1	54.6	52.3	52.7	54.5	55.4	54.2
120	40.3	55.4	58.0	57.4	55.6	54.4	55.1	56.1	55.2
135	41.5	58.2	60.4	59.8	58.0	56.0	56.0	57.1	57.1
150	41.9	59.8	61.6	60.7	59.5	57.0	56.6	58.3	58.9
165	42.6	60.5	62.6	61.2	60.2	57.5	57.1	59.0	59.8
180	42.6	60.9	62.7	61.2	60.2	57.6	57.5	59.2	59.9
195	42.3	60.5	62.4	60.4	59.8	57.2	57.5	58.7	59.1
210	41.0	59.4	61.3	59.0	58.5	56.3	57.1	57.5	57.8
225	40.4	57.8	60.2	57.3	57.2	55.4	56.7	56.6	56.6
240	39.1	55.9	58.4	55.0	55.1	54.2	56.1	55.9	55.3
255	36.6	51.1	55.5	50.8	51.0	52.3	54.9	55.5	54.7
270	35.8	42.7	53.8	50.2	48.5	51.7	54.2	55.2	54.1
285	36.2	47.8	55.9	53.9	51.4	52.3	53.7	55.2	54.2
300	37.4	54.0	58.2	57.1	54.6	53.6	54.5	55.5	55.1
315	38.5	56.5	60.0	59.0	56.9	55.2	55.7	56.7	56.8
330	40.0	58.3	61.5	60.3	58.6	56.2	56.9	57.8	58.5
345	40.5	59.2	62.3	61.0	59.3	57.0	57.6	58.6	59.5
Mean (Z)	39.4	55.5	59.3	57.1	55.9	54.9	56.0	56.9	56.8

APPENDIX B

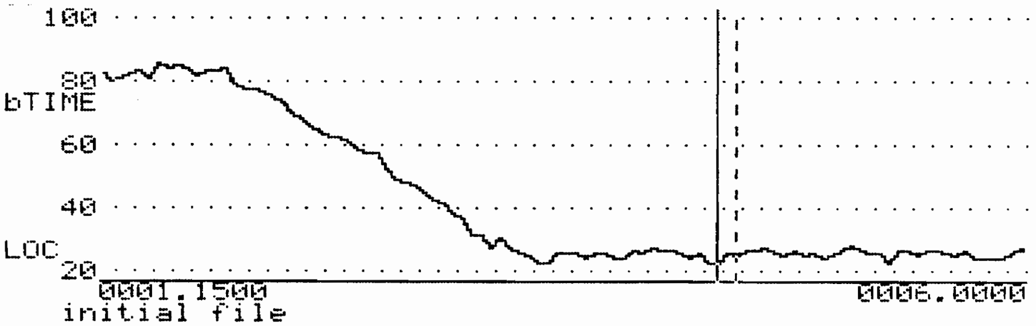
Reverberation Time Decay Curves



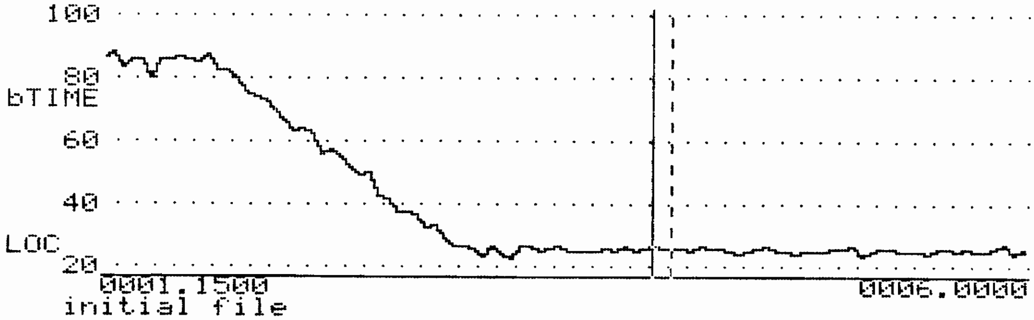
Decay curve for 125 Hz 1/3 OB test signal in reverberant, three-speaker sound field. (Distance between vertical lines represents 0.1 s.)



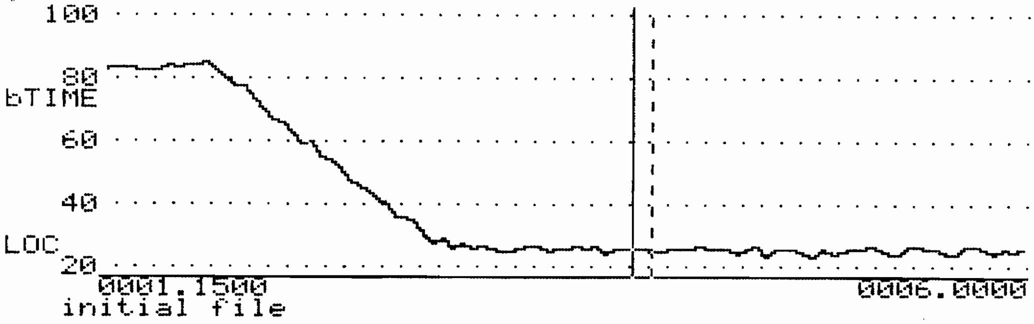
Decay curve for 250 Hz 1/3 OB test signal in reverberant, three-speaker sound field. (Distance between vertical lines represents 0.1 s.)



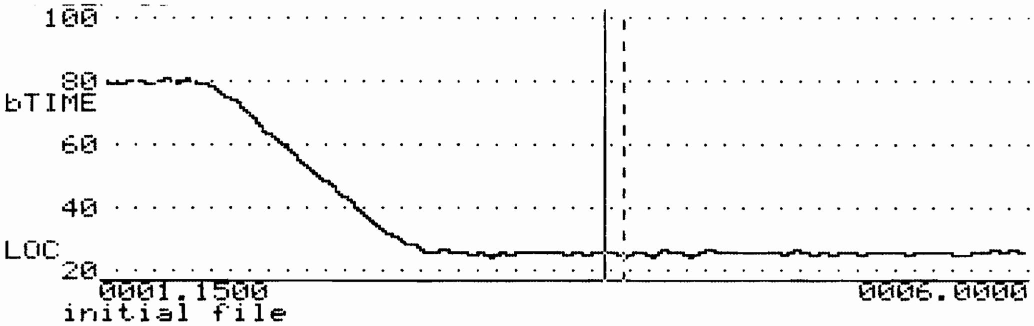
Decay curve for 500 Hz 1/3 OB test signal in reverberant, three-speaker sound field. (Distance between vertical lines represents 0.1 s.)



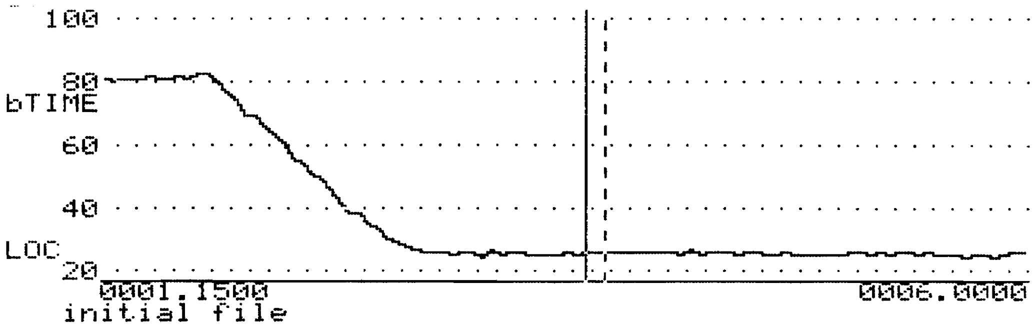
Decay curve for 1000 Hz 1/3 OB test signal in reverberant, three-speaker sound field. (Distance between vertical lines represents 0.1 s.)



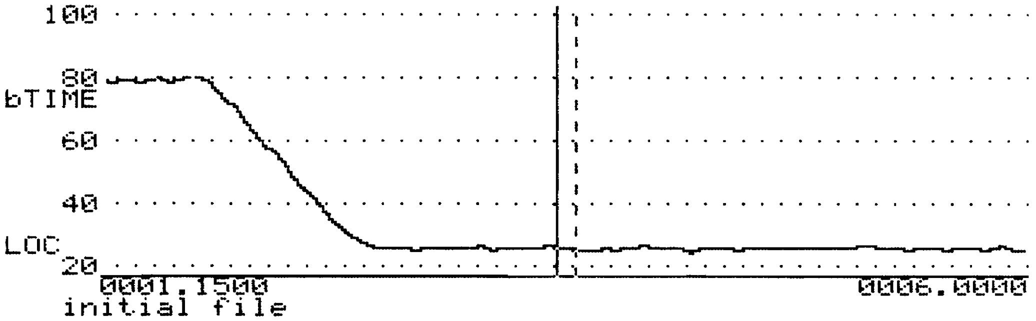
Decay curve for 2000 Hz 1/3 OB test signal in reverberant, three-speaker sound field. (Distance between vertical lines represents 0.1 s.)



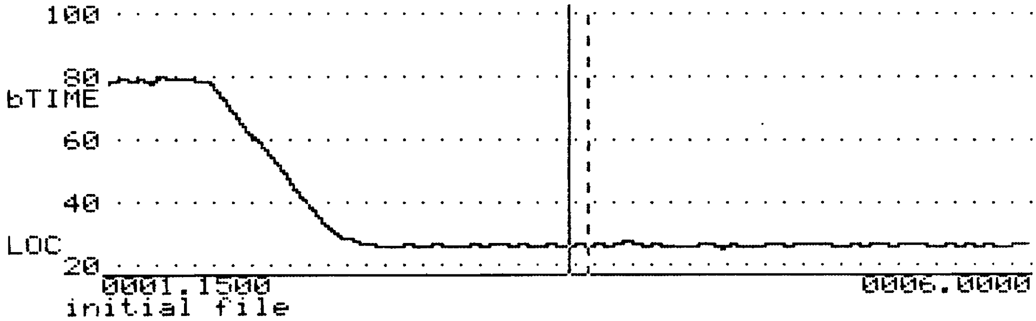
Decay curve for 3150 Hz 1/3 OB test signal in reverberant, three-speaker sound field. (Distance between vertical lines represents 0.1 s.)



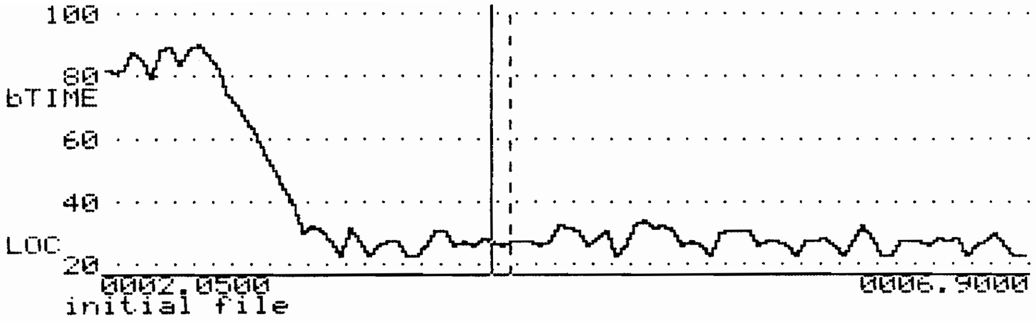
Decay curve for 4000 Hz 1/3 OB test signal in reverberant, three-speaker sound field. (Distance between vertical lines represents 0.1 s.)



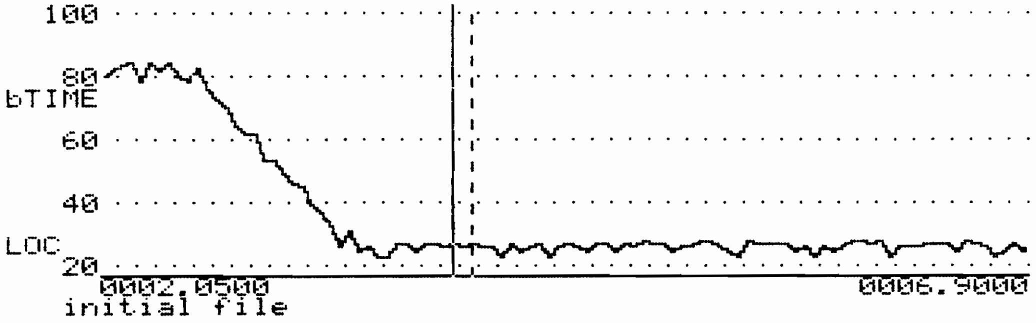
Decay curve for 6300 Hz 1/3 OB test signal in reverberant, three-speaker sound field. (Distance between vertical lines represents 0.1 s.)



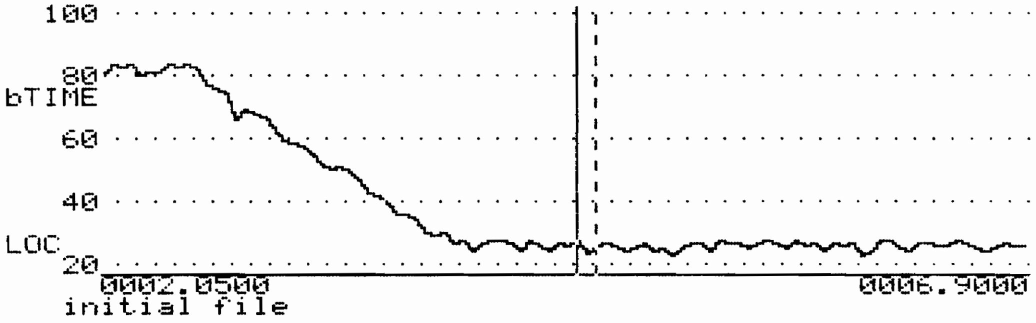
Decay curve for 8000 Hz 1/3 OB test signal in reverberant, three-speaker sound field. (Distance between vertical lines represents 0.1 s.)



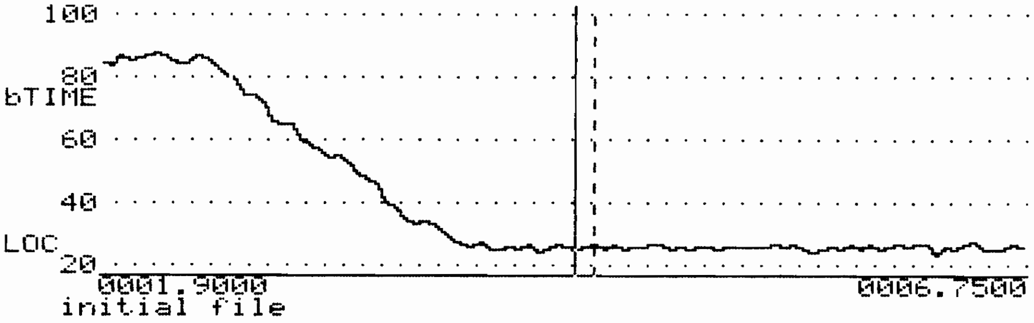
Decay curve for 125 Hz 1/3 OB test signal in reverberant, one-speaker sound field. (Distance between vertical lines represents 0.1 s.)



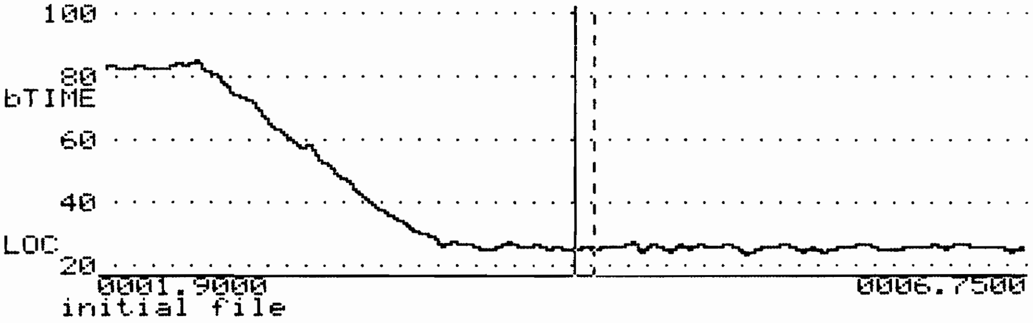
Decay curve for 250 Hz 1/3 OB test signal in reverberant, one-speaker sound field. (Distance between vertical lines represents 0.1 s.)



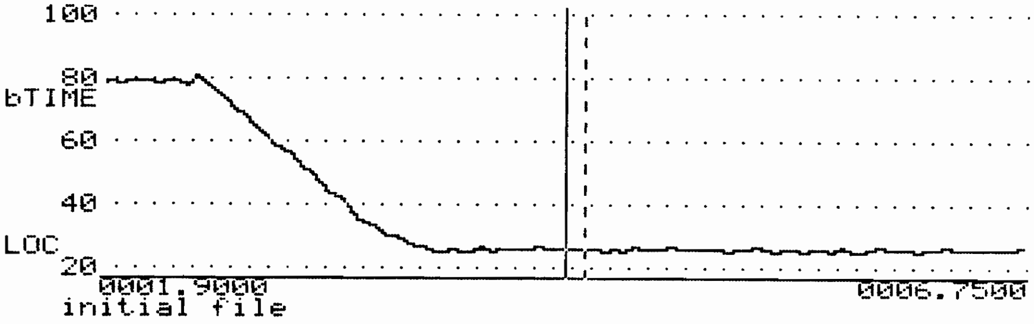
Decay curve for 500 Hz 1/3 OB test signal in reverberant, one-speaker sound field. (Distance between vertical lines represents 0.1 s.)



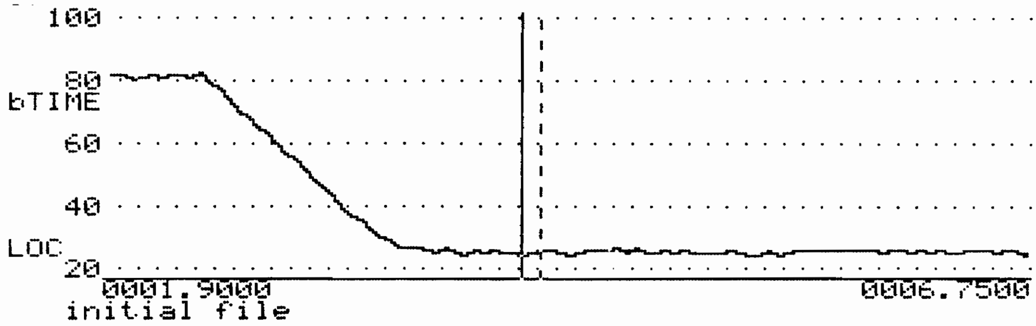
Decay curve for 1000 Hz 1/3 OB test signal in reverberant, one-speaker sound field. (Distance between vertical lines represents 0.1 s.)



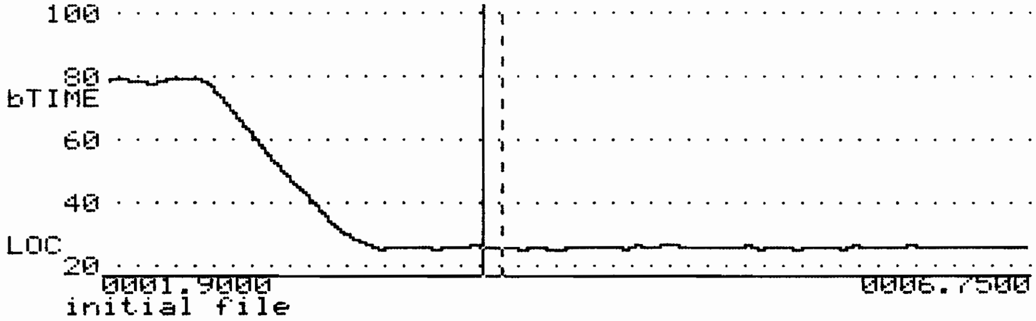
Decay curve for 2000 Hz 1/3 OB test signal in reverberant, one-speaker sound field. (Distance between vertical lines represents 0.1 s.)



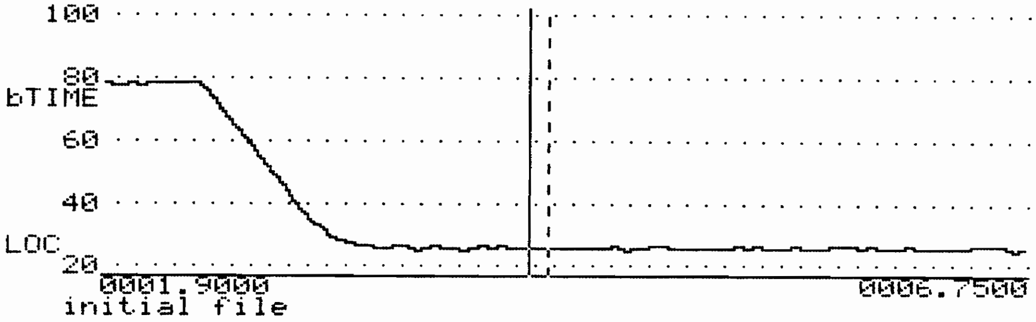
Decay curve for 3150 Hz 1/3 OB test signal in reverberant, one-speaker sound field. (Distance between vertical lines represents 0.1 s.)



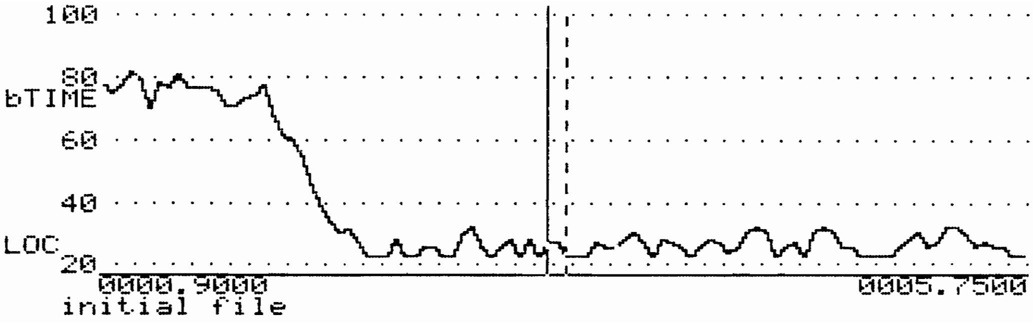
Decay curve for 4000 Hz 1/3 OB test signal in reverberant, one-speaker sound field. (Distance between vertical lines represents 0.1 s.)



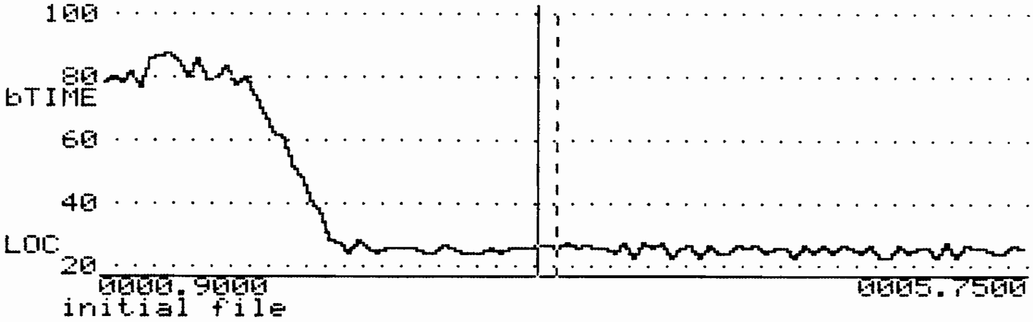
Decay curve for 6300 Hz 1/3 OB test signal in reverberant, one-speaker sound field. (Distance between vertical lines represents 0.1 s.)



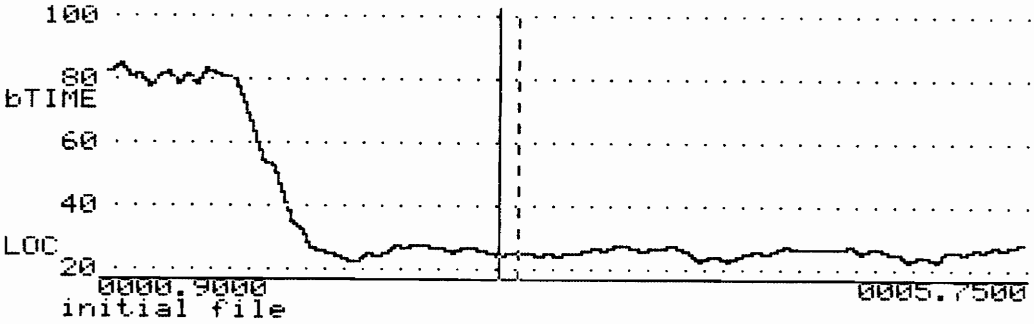
Decay curve for 8000 Hz 1/3 OB test signal in reverberant, one-speaker sound field. (Distance between vertical lines represents 0.1 s.)



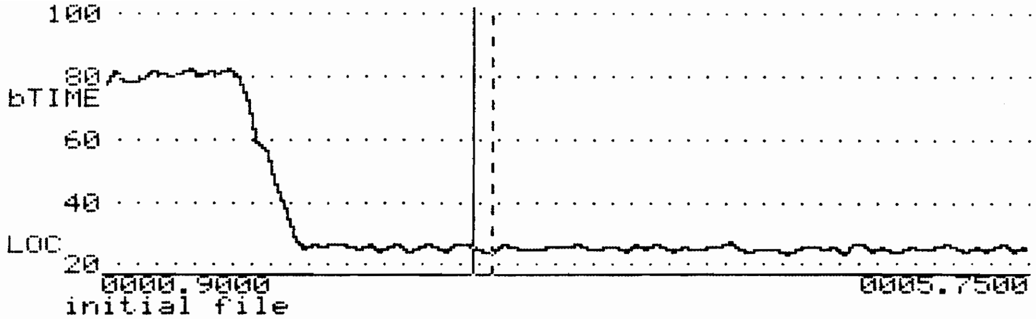
Decay curve for 125 Hz 1/3 OB test signal in semi-reverberant sound field. (Distance between vertical lines represents 0.1 s.)



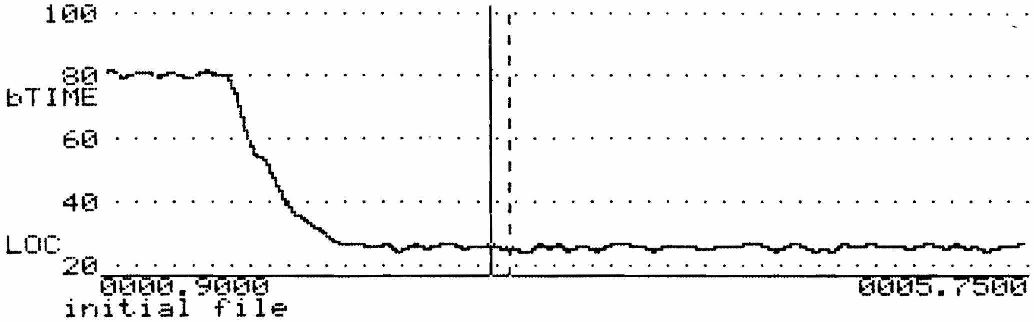
Decay curve for 250 Hz 1/3 OB test signal in semi-reverberant sound field. (Distance between vertical lines represents 0.1 s.)



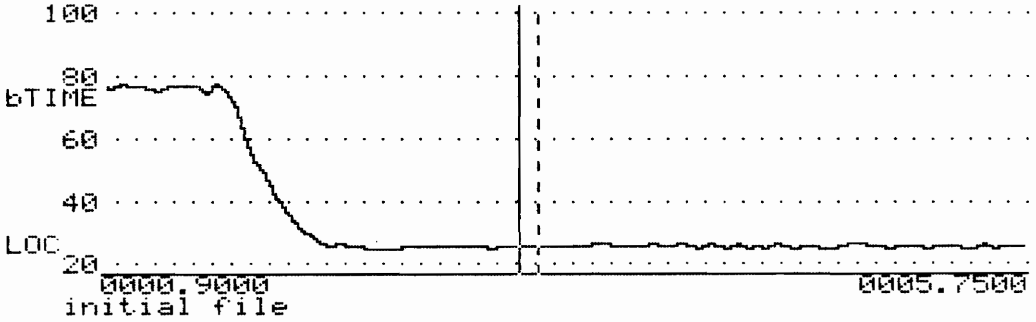
Decay curve for 500 Hz 1/3 OB test signal in semi-reverberant sound field. (Distance between vertical lines represents 0.1 s.)



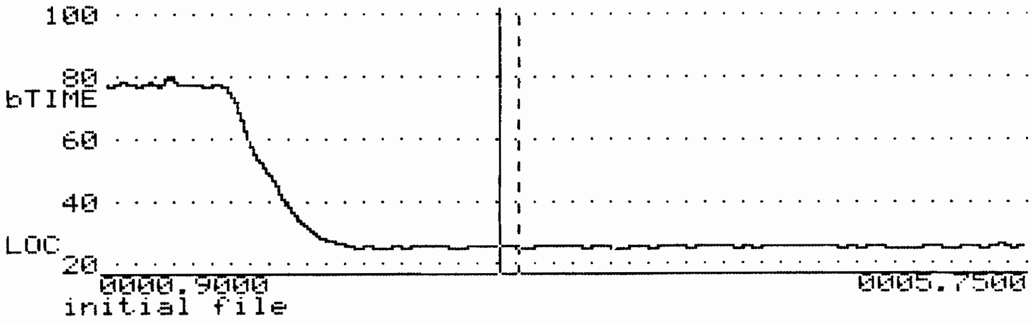
Decay curve for 1000 Hz 1/3 OB test signal in semi-reverberant sound field. (Distance between vertical lines represents 0.1 s.)



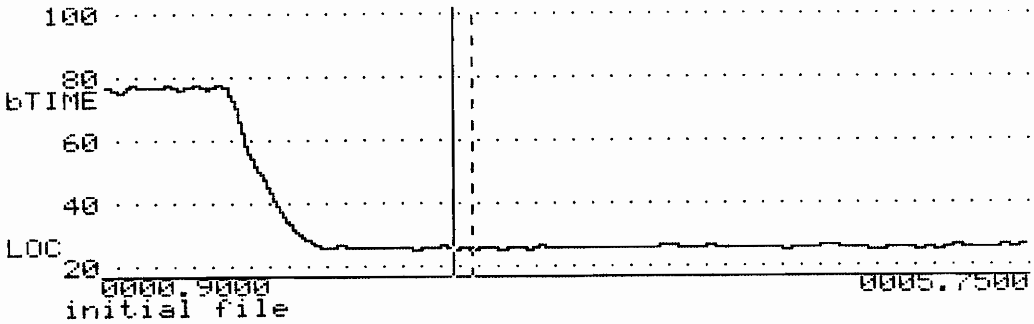
Decay curve for 2000 Hz 1/3 OB test signal in semi-reverberant sound field. (Distance between vertical lines represents 0.1 s.)



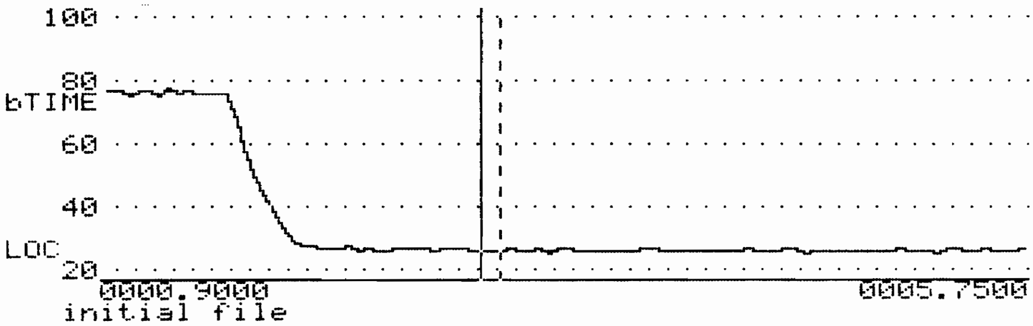
Decay curve for 3150 Hz 1/3 OB test signal in semi-reverberant sound field. (Distance between vertical lines represents 0.1 s.)



Decay curve for 4000 Hz 1/3 OB test signal in semi-reverberant sound field. (Distance between vertical lines represents 0.1 s.)



Decay curve for 6300 Hz 1/3 OB test signal in semi-reverberant sound field. (Distance between vertical lines represents 0.1 s.)



Decay curve for 8000 Hz 1/3 OB test signal in semi-reverberant sound field. (Distance between vertical lines represents 0.1 s.)

APPENDIX C

Experimental Description

This experiment is designed to investigate the attenuation (protective effectiveness) of hearing protection devices (HPDs) as measured in the laboratory. In the portion of the experiment in which you will be taking part, 17 earmuffs and one set of earplugs will be tested.

You will attend one initial screening session and at least 15 experimental sessions. Depending on the results of post-hoc (after data collection) statistical tests, it may be necessary to retest you on one or more of the devices in one or both test spaces. A total of six devices are to be tested in the reverberant environment, three of which will be tested three times. However, three of these devices will also be tested in the anechoic environment. Therefore, there will be a minimum of 15 sessions. The maximum number of sessions that will be required of you is 23. It is highly unlikely, however, that it will be necessary for anyone to take part in 23 sessions. In the event that retesting is required, you will be contacted by the experimenter to schedule the additional session(s). You will be paid $6.00 per hour for each experimental session. The money will be paid to you at the end of the 15th session.

The screening session will consist of your being asked questions (or alternatively, filling out a questionnaire) concerning your hearing and past experience with hearing protection devices; being presented with an informed consent form; having your outer ears visually examined; having your ear canal size, ear size (height and width), and your bitragus breadth (distance between your ears) measured; undergoing the administration of a hearing test; and if necessary, participating in an experience-leveling procedure which consists of conducting at least six open-ear threshold measurements in the reverberant test space. The entire screening session is expected to take approximately one hour to complete. If you qualify on the hearing test (which will be conducted first), you will proceed with the remainder of the screening session and will be paid for the session.

Each experimental session will consist of conducting a total of six hearing thresholds in one of the two test spaces. Three of the thresholds will be in the unoccluded (open-ear) condition and three will be in the occluded (wearing an HPD) condition. In all cases in which an HPD is worn, the device will be fitted by the experimenter. While wearing the HPD, you are asked to refrain from touching or adjusting the device and not to talk or otherwise move your jaw unnecessarily. No risk is posed by the experiment except the possibility of fatigue due to the length of the experimental session and perhaps some minor discomfort because of the tight fit of the protectors, but the devices will not harm you in any permanent way.

APPENDIX D

Informed Consent Form

SUBJECT'S INFORMED CONSENT

AUDITORY SYSTEMS LABORATORY-VA TECH
(AUDIOMETRY AND/OR HEARING PROTECTION DEVICE ATTENUATION TEST)

First, your right and left ear hearing will be tested with very quiet tones played through a set of headphones. Then, if qualified, you may also participate in a research experiment designed to investigate your hearing ability in two conditions: 1) while wearing a hearing protector, and 2) while your ears are uncovered. In both conditions your hearing will be tested with very quiet pulsating tones played through a set of loudspeakers. You will have to be very attentive and listen carefully for these tones. **Depress the button on the hand switch and hold it down whenever you can hear the tone and release it when you do not hear a tone.** The tones will be very faint and you will have to listen very carefully to hear them.

No loud or harmful sounds will ever occur during the study. The test will be conducted in a sound-proof booth with the experimenter sitting outside. The door to the booth will be shut but not locked; either you may open it from the inside or the experimenter may open it from the outside. There is also an intercom system through which you may communicate with the experimenter by simply talking. (There are no buttons to push.)

There is no risk to your well-being posed by these hearing tests. Also, realize that they are not designed to assess or diagnose any physiological or anatomical hearing disorders. The tests will only be used to determine your hearing ability today.

The purpose of the study is to determine the optimal attenuation (i.e., noise reduction) capabilities of several hearing protectors, including earplugs, earmuffs, and ear canal caps. You will be asked to wear several protectors during the course of the study. You will either fit the protectors on yourself with the experimenter's supervision, or alternatively, the experimenter may fit the protectors on you. The protectors are intended to provide a snug fit so that noise will be blocked. Therefore, they may seem tight in or around your ears. Some minor discomfort may result from the tight fit, but the protectors will not in any way damage your hearing ability.

Several physical measurements may also be obtained as a part of the study. These will include dimensional measurements of the ear and head width, obtained with simple rulers, calipers, and an ear gauge. None of these screening procedures pose any risk to your well-being or cause any pain. If you desire, the experimenter will show you the measurement instruments at this time.

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

1) You have the right to discontinue participating in the study at any time for any reason by simply informing a member of the research team.

2) You have the right to inspect your data and to withdraw it from the experiment if you feel that you should. In general, data are processed and analyzed after all subjects

have completed the experiment. Subsequently, your data will be kept confidential by the research team. No one else will see your individual data with your name.

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

4) You may ask questions of the research team at any time prior to data collection. All questions will be answered to your satisfaction subject only to the constraint that an answer will not prebias the outcome of the study. If bias would occur, with your permission an answer will be delayed until after data collection, at which time a full answer will be given.

Before you sign this form, please make sure that you understand, to your complete satisfaction, the nature of the study and your rights as a participant. If you have any questions, please ask them of the experimenter at this time. Then if you decide to participate, please sign your name below and provide your phone number so that you may be contacted for scheduling.

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

Signature ____

Printed Name ____

Date ____

Phone ____

REMEMBER, you are supposed to press the button (and keep it pressed) whenever you hear the tone and release it when you do not hear the tone.

The research team for this experiment consists of Gary Robinson and Dan Mauney, graduate students in ISE, and Dr. John G. Casali, Director of the Auditory Systems Laboratory. They may be reached at the following address and phone number:

Auditory Systems Laboratory
Room 538 Whittemore Hall
VPI&SU
Blacksburg, VA 24061
(703) 231-9086

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

Dr. Ernie Stout
Chairman, University Human Subjects Committee
301 Burruss Hall
VPI&SU
Blacksburg, VA 24061
(703) 231-5283

(PLEASE TEAR OFF AND KEEP THIS PAGE FOR FUTURE REFERENCE.)

VITA

Mr. Daniel W. Mauney, born November 19, 1966, received his B. S. in Industrial Engineering and Operations Research at Virginia Polytechnic Institute and State University (VPI & SU) in May, 1989. Upon completion of his M. S. degree in Industrial and Systems Engineering at VPI & SU with a concentration in human factors, he intends to pursue a Ph.D. in the same field

While attending VPI & SU, he served as an instructor for a Work Measurement and Methods Engineering class and as a graduate teaching assistant for courses in Introduction to Human Factors and Engineering Economy. His primary research concentration has been in human audition, serving as a graduate research assistant in the Auditory Systems Laboratory. During this time, he has applied for a patent on an innovative, custom-fitting ear insert for use as a hearing protector, hearing aid coupler, and communications earpiece coupler. His research interests include auditory systems/personal hearing protection and displays and controls.

He has many outside interests, including whitewater kayaking, hiking, skiing, camping, and canoeing. In addition, he has been heavily involved with coaching soccer and enjoys playing many sports.