Field Evaluation of Noise Attenuation and Comfort Performance of Earplug, Earmuff, and Ear Canal Cap Hearing Protectors Under the ANSI S12.6-1984 Sound Field Standard

by

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(ABSTRACT)

A field research study was conducted to determine the actual noise attenuation and perceived comfort achieved by 40 noise-exposed industrial workers in 5 industrial workplaces wearing 4 different industrial hearing protection devices (HPDs) while on the job. Over 2 consecutive 3-week periods of HPD use, the study investigated the effects of 2 different HPD fitting procedures (subject-fit versus trained-fit) on the spectral field attenuation and user-rated comfort achieved with a user-molded foam earplug, a premolded, triple-flanged polymer earplug, a popular foam cushion earmuff, and an ear canal cap with compliant rubber earpods. Workers were pulled from their workplaces without prior knowledge of when they were to be tested and without re-adjusting the fit of their HPDs. Attenuation data were collected using psychophysical real-ear-attenuation-at-threshold measurement procedures as per the ANSI S12.6-1984 standard. Subjective comfort data were also obtained based on multi-dimensional bipolar rating scales. The results of statistical analyses indicated that when training for proper fitting was used, the earplugs significantly improved in noise protection (from 7.2 to 14.6 dB, depending on the frequency and the earplug) at frequencies of 125 - 1000, 6300, and 8000 Hz, whereas the earmuff and the ear canal cap were relatively resistant to the fitting effect. The training was most effective for

the slow-recovery foam earplug over the 3-week period. For the comfort rating data, the foam earplug was again sensitive to the fitting effect, but the other HPDs were not. Among the 4 HPDs evaluated in the study, the canal cap protector was judged as the least comfortable HPD, while the other 3 HPDs yielded about the same perceived comfort. This research also showed that the overall field HPD protection afforded can be accurately predicted from single test band (i.e., centered at 500 or 1000 Hz) attenuation measurements. In addition, the field study demonstrated that laboratory simulation protocols designed to simulate field influences on HPD performance (used in the precursor laboratory study) may not be relied upon to yield accurate estimates of field performance of all HPDs. However, the estimates of field attenuation performance were more accurate for the earmuff than for the earplugs tested. Finally, this study demonstrated that the labeled manufacturers' single-number noise reduction ratings (NRRs) and frequency-specific data substantially overestimate the actual HPD attenuation performance achieved in the field. Consequently, on the basis of the results of this study, it appears that an appropriate, device-specific derating scheme to correct unrealistic labeled attenuation data is needed.

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ANOVA	analysis of variance
ANSI	American National Standards Institute
AT	above threshold
AT500	1/3-octave band attenuation measurement at 500 Hz
AT1000	1/3-octave band attenuation measurement at 1000 Hz
BSI	British Standard Institute
CCTV	closed-circuit television
CI	Comfort Index
dBA	decibel (dB) level with A-weighted filter
dBC	decibel (dB) level with C-weighted filter
dBHL	hearing threshold level in dB
EAL	Environmental Acoustic Laboratory
EPA	Environmental Protection Agency
FS	field subject-fit
FT	field trained-fit
HCA	Hearing Conservation Amendment
HCP	hearing conservation program

HL	hearing level
HPD	hearing protection device
HTL	hearing threshold level
IAC	Industrial Acoustics Corporation
ISO	International Standards Organization
LS	laboratory subject-fit
LT	laboratory trained-fit
MAF	minimum audible field
ML	midline laterlization
MRE	microphone in real ear
NIHL	noise-induced hearing loss
NIOSH	National Institute for Occupational Safety and Health
NIPTS	noise-induced permanent threshold shift
NRR	Noise Reduction Rating (= NRR$_{98}$)
NRR$_{PS}$	NRR per subject (0 σ-corrected)
NRR$_{84}$	NRR estimate for 84% of population (1 σ-corrected)
NRR$_{98}$	NRR estimate for 98% of population (2 σ-corrected)
OB	octave-band
OSHA	Occupational Safety and Health Administration
PI	prediction interval

PTS	permanent threshold shift
REAT	real-ear-attenuation-at-threshold
RW NRR_{84}	real-world NRR_{84}
SD	standard deviation
SPL	sound pressure level
TTS	temporary threshold shift
TWA	time-weighted average
VPI	Virginia Polytechnic Institute (Virginia Tech)

INTRODUCTION

Background

One of the major stresses with which industrial workers must cope is excessive noise exposure. Ever since a law was passed in ancient Greece barring metal-work hammering in a populated area (Woodford, 1981), it has been recognized that high intensity noise from an industrial environment constantly threatens workers' hearing (Suter, 1986). As evidence, over 9.2 million American workers are exposed to daily average noise levels of above 85 dBA (EPA, 1981), and more than one million workers in the manufacturing industry alone have sustained job-related hearing impairment (Haag, 1988).

Noise-induced permanent threshold shift (NIPTS), or noise-induced hearing loss (NIHL), usually results from extended exposure of the unprotected ear to loud noise, although it may immediately occur after sudden acoustic trauma. Although occupational NIHL is preventable, its debilitating effects are often quite insidious and pervasive and may not be noticed by the victim until it is too late for recovery. Also, worker compensation for occupational NIHL has become a major expense in industry (Sataloff, 1984; Robinette, 1984), and the increasing trend may continue unless effective counteractions are taken. Consequently, management and safety personnel in industry establish and maintain hearing conservation programs, as mandated by the Occupational Safety and Health Act (OSHA, 1988). According to the Hearing Conservation Amendment of OSHA, for workers who are in areas for which the 8-hour TWA (time-weighted average) of noise equals or exceeds 85 dBA, an audiometric program must be maintained, and hearing protection devices (HPDs) are required to be supplied to the workers. Furthermore, at the 85 dBA TWA level, if a worker exhibits hearing loss, protectors are also required to be worn.

HPDs are currently the most popular countermeasure against NIHL, and four major types of currently available HPDs include earplugs, earmuffs, ear canal caps, and helmets. The decision to select a specific HPD typically depends on its noise reduction characteristics, comfort achieved, cost, and durability.

Research Issues Underlying the Current Study

HPDs differ widely in their noise attenuation capabilities (e.g., Berger, 1980a, 1986a; Casali, 1986; Lempert and Edwards, 1983; Royster, 1980), in their user comfort (e.g., Casali, Lam, and Epps, 1987; Mimpen, 1987; Sweetland, 1981), and therefore, largely due to these two factors, in their utility and efficacy. It has been empirically demonstrated that the field performance of HPDs is significantly less than that estimated by standardized laboratory measurement methods (e.g., Lempert and Edwards, 1983; Regan, 1978). This often large discrepancy between field and laboratory HPD performance is attributed to the fact that optimum performance for a laboratory test is very different from the performance that can be achieved in the real world where many field factors may degrade HPD performance.

Several field studies (e.g., Behar, 1985; Edwards and Green, 1987; Lempert and Edwards, 1983; Padilla, 1976; Regan, 1978) have assessed actual HPD performance (i.e., noise attenuation/comfort) achieved under field conditions. However, according to a review by Berger (1983), earplugs have been predominantly used for that purpose, and few earmuffs and ear canal caps have been in-field tested using the real-ear attenuation at threshold (REAT) procedure (e.g., Behar and Desormeaux, 1986). Also, little attention has been directed to investigate the effect of HPD fitting procedure (i.e., user-fit versus trained-fit) in the field setting, although a few studies have been conducted in controlled laboratory settings (e.g., Casali and Epps, 1986; Casali and Lam, 1986a; Casali and Park, 1990a).

The objective of this field study was to assess how much HPD field performance differs from laboratory-estimated HPD performance achieved by various industrial HPDs, including two earplugs, an earmuff, and an ear canal cap. The research, the second phase of a NIOSH-funded two-year HPD study, concentrated on determining the actual spectral noise attenuation and perceived comfort achieved by workers wearing selected HPDs while on the job. The results from the study were also compared to the performance (i.e., attenuation and comfort) achieved by identical HPDs used in the earlier laboratory simulation study (Park, 1989), the first phase of the NIOSH-funded HPD study conducted at Virginia Tech. In this manner, the *validity* of estimating real-world HPD performance under laboratory simulation conditions could be ascertained as a side benefit of the study. This is a major advantage of conducting similar experimental designs in both laboratory and field environments.

With these research aims in mind, the dissertation follows with a literature review discussing the known auditory effects of hazardous industrial noise on workers' hearing, and an overview of industrial HPDs, including their noise reduction characteristics and factors associated with their field effectiveness. Various methods of measuring and estimating HPD attenuation, as well as research on field HPD performance, are also reviewed. The experimental design and research methodology are next presented, followed with the results and discussion. Finally, conclusions and recommendations for future research are addressed.

Noise Hazards to Human Hearing

"... blest are your ears because they hear." (Matthew 13:16)

Noise is any undesired sound or sound of random nature which may be steady, nonsteady, or impulsive (ANSI, 1973). Noise is perhaps the most ubiquitous pollutant in the human life. It affects almost everyone at times -- not only workers in noisy industrial environments or city dwellers who suffer from the noise of traffic and overflying aircraft, but also the inhabitants of rural areas, who are exposed to noise from farm machinery, gunfire (if they are hunters or target shooters), or even automobile racing.

The effects of noise on humans may be divided into two categories: auditory effects, which primarily relate to hearing damage or loss, and nonauditory effects, which include noise annoyance, behavioral and physiological effects, sleep disturbance, and interference in speech communication. Excellent reviews of the nonauditory effects of noise appear in Dejoy (1984) and Miller (1974). Due to their significance in the current research, only auditory effects of noise are addressed in this review, along with a brief discussion of the fundamental human hearing mechanism.

Human hearing mechanism

The human ear has three primary sections: the *outer ear*, which includes the appendage which is normally called the ear and its canal; the *middle ear*, beginning with the eardrum and including the ossicles, the ear muscles, the mastoid space and bone, and the Eustachian tubes; and the *inner ear*, consisting of the cochlea and the vestibular organs. Figure 1 illustrates a sagittal cross section of the ear.

Sound is received by the cartilaginous structure of the outer ear (i.e., pinna) and eventually reaches the inner ear through both air and bone conduction pathways. The middle ear includes the ossicles, the three smallest bones of the human body (the malleus or hammer, the incus or anvil, and the stapes or stirrup), and is the major conductive mechanism. The vibration of fluid in the inner ear stimulates hairlike nerve cells, called cilia, thus generating nerve signals (electrical impulses). These signals are transmitted along the auditory nerve to the brain, where they are decoded. More detailed discussion of the anatomy and physiological/sensory function of the human ear may be found in Loeb (1986) and Olishifski (1988).

The natural defense mechanism of the middle ear has a limited capability for protecting the neural portion of the inner ear from intense noise. The response of the intratympanic muscles (the stapedius and the tensor tympani muscles) to intense sounds, often called the "acoustic reflex," limits the motion of the ossicles and thereby helps protect the inner ear from damage by intense sound. It is generally accepted that the acoustic reflex of the human ear is due mainly to contraction of the stapedius (Gelfand, 1981; Rossing, 1990); the tensor responds only to extremely intense sounds, and also as part of a startle response. According to Rossing (1990), since the full response time of the acoustic reflex may be as long as 200 ms, the reflex does not adequately protect the inner ear from impulsive or explosive sounds with extremely fast rise and fall time.

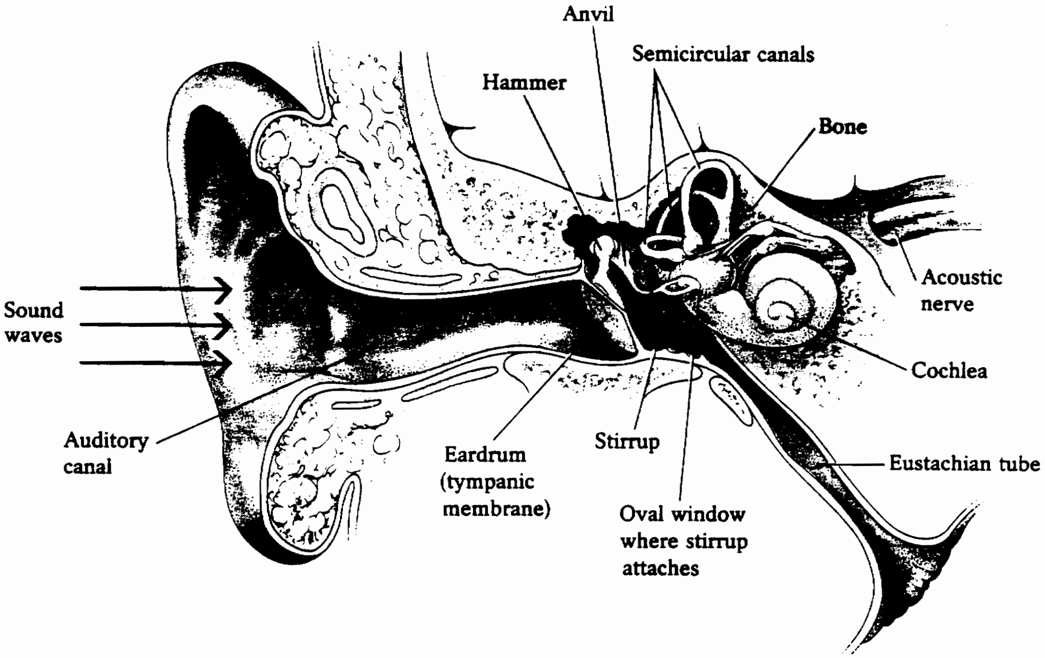

Figure 1. Basic anatomy of the ear: (Lindzey, Thompson, and Spring, 1988, p. 103 - reproduced with permission).

Noise-induced hearing loss (NIHL)

As Miller (1978) indicated, more people suffer occupational NIHL than all other job-related diseases totalled. The primary site of auditory injury from exposure to industrial noise for prolonged periods is the organ of Corti in the inner ear. This neural hearing loss results from destruction of hair cells and auditory neurons, collapse of sections of the organ of Corti, and, ultimately, injury to the auditory nerve (Miller, 1974). Greater hearing loss is generally most prominent at the higher frequencies, particularly if the etiology is the aging process (such loss is termed "presbycusis"). Nerve deafness, resulting from the neural hearing loss, is generally thought to be incurable.

Exposure to intense noise for a relatively short time may lead to short-term hearing loss, namely, noise-induced temporary threshold shift (TTS). This hearing sensitivity loss, due to a "desensitized" ear and sometimes referred to as "auditory fatigue," occurs especially at frequencies around 4000 Hz (Rossing, 1990), and the threshold will shift back to normal with time away from the noise. Prolonged or repeated exposure may, however, cause a noise-induced permanent threshold shift (PTS or NIPTS). Thus, in general, the occurrence of TTS must be considered as a warning for the existence of a harmful noise environment.

On the other hand, permanent threshold shift (PTS), also called noise-induced permanent threshold shift (NIPTS), is typically caused by repeated or extended exposure to loud noise and the resulting irreversible anatomical changes in the organ of Corti. Like TTS, PTS is usually maximal at frequencies around 4000 Hz. In the early stages, the threshold shift is usually constrained to frequencies between 2000 and 8000 Hz, but the shift continues to grow and the affected range of frequencies gets broader (Rossing, 1990; Tempest, 1985). PTS may also be attributed to presbycusis (as well as other causes), and often the etiology of the loss is difficult to determine in a post-hoc sense. More details on the development of NIHL appear elsewhere (e.g., Miller, 1974; Olishifski, 1988; Robinson, 1976).

HEARING PROTECTION DEVICES

For the systems approach (source-path-receiver) to noise abatement (Bolt and Ingard, 1957), three types of noise control strategies may be employed: engineering controls, administrative controls, and personal hearing protection devices (HPDs). Although engineering controls (e.g., protection by machine enclosures) are the most preferred because of reliability, they are often infeasible due to cost, productivity, or mechanical maintenance problems (Casali, 1986). Also, administrative controls (e.g., job rotation among noisy and less-noisy jobs) are often difficult to enforce and may create the risk of spreading a slight hearing loss among all workers in the rotation.

On the other hand, HPDs, the final type of control strategy, are relatively cheap, easily obtainable, and readily applicable to a large industrial workforce. For these reasons, they are presently the most popular measure for noise protection. However, HPDs must be carefully selected, administered, and monitored for maximum effectiveness to be realized. The next section provides an overview of industrial HPDs.

Types of HPDs

There are four types of HPDs on the current market: aural (in the ear canal) earplugs, semi-aural (concha-seated) earcaps or ear canal caps, circumaural (over the pinna) earmuffs, and helmets (enclosures). Currently, earplugs, earmuffs, and earcaps are the most common industrial HPDs. (Since helmets, which may be used in certain extremely high noise conditions such as when skull conduction is a problem, are not often used in the industrial setting, they are not further addressed here.) Detailed descriptions of each HPD type can be found in various articles (e.g., Berger, 1986a; Casali, 1986; Nixon, 1979; Zwislocki, 1957).

Earplugs

Earplugs (or aural inserts) are the most commonly applied HPD in industry because they can generally provide adequate noise reduction for most applications with relatively low cost. Although their effectiveness is usually not degraded by the presence of hair, eyeglasses, hats, and ear jewelry, earplugs are not the best choice for certain workers who have sensitive, irregularly shaped ear canals, or excessive ear wax. Also, proper sizing and insertion instruction are critical for obtaining adequate attenuation performance with most earplugs (Casali and Epps, 1986).

The three major types of earplugs are user-molded, premolded, and custom-molded. The user-molded earplug (or a formable plug) is made from malleable foam polymer, mineral fiber, wax, or wax-impregnated cotton, and is formed by the user to fit each individual ear. User-molded (usually disposable) earplugs can generally achieve satisfactory attenuation while affording comfort, less maintenance, and low cost. Furthermore, the performance of foam plugs may be insensitive to worker movement or long wearing periods (Casali and Park, 1990b). On the other hand, the premolded earplug (made of silicon, rubber, mineral fiber, or plastic) and the custom-molded earplug (a rubber or silicon mold of the wearer's ear canal) have somewhat specific maintenance requirements, e.g., regular cleansing and proper storage (Berger, 1986a; Nixon, 1979). The premolded earplug is available in one universal size or, in a few cases, multiple sizes.

Earmuffs

Earmuffs consist of a headband attached to two earcups with cushions which enclose the pinna and seal against the head. In general, earmuffs are more durable, more easily donned, and some examples offer greater protection than earplugs at high frequencies (Miller, 1978; Willson, 1985). This may be because the acoustical resistance is consistent with optimum cavity damping of the cup component of earmuffs at frequencies greater 2000 Hz (Shaw, 1982). In contrast, many earplugs have an attenuation advantage over earmuffs at low frequencies below 1000 Hz due to the fact that the stiffness and effective mass of earplugs (resulting from earplugs' contact with the ear canal walls) affect more pronouncedly low frequency (i.e., 1000 Hz or below) attenuation than that achieved at high frequencies (Zwislocki, 1957).

Earmuffs have advantages in environments with hygiene problems where dirty hands might contaminate insert protectors and where HPD monitoring is essential. Also, due to their straightforward fitting requirements and ease of donning/doffing, earmuffs can be expected to achieve more reliable (or less variable) protection than earplugs in some cases, particularly where worker supervision is at a minimum (Casali and Lam, 1986; Willson, 1985). However, earmuffs are somewhat cumbersome due to their bulky structure, are affected by hair, eyeglasses, and earrings, may feel hot (although this may be an advantage in cold environments), and require periodic maintenance and parts replacement.

The effectiveness of earmuffs generally depends upon the size/volume and shape of the earcups, the area and the filler substance (liquid and/or foam) of the cushion, the headband adjustability and compression force, the mass of the earcups, and the physical features of the wearer's head. Several authors (e.g., Botsford, 1972;

Grenell, 1988; Nixon, 1979; Savich, 1982; Zwislocki, 1957) have addressed these factors as they impact earmuff effectiveness.

Ear canal caps

Ear canal caps, also called earcaps, are semi-aural devices, which consist of pods or flexible tips attached to a lightweight metal or plastic headband, which seal the opening of the ear canal at its rim. Due to their ability to be quickly taken on and off and also the ease with which they can be stored around the neck, earcaps are ideal for intermittent use. Earcaps may also be ideal for application in warm environments where the use of earmuffs may cause discomfort due to heat buildup beneath the earcups. In addition, hair and devices worn on the head also typically interfere less with earcaps than with earmuffs.

On the other hand, since earcaps generally cap the canal at or near its entrance, they tend to create the most noticeable "occlusion effect" (to be explained) and consequently distort the wearers' perception of their own speech more than other types of HPDs (Berger, 1986a, 1988a). Furthermore, workers may complain of discomfort caused by wearing earcaps for extended periods due to pressure exerted on the outer rim of the ear canal (Botsford, 1972; Casali and Lam, 1986). Like earmuffs, they also need regular maintenance, parts replacement, and storage. Due to the aforementioned drawbacks and their relatively high cost compared to earplugs, earcaps are currently the least popular HPD for industrial use.

Physics of HPD Performance

The acoustical performance of an HPD is influenced by the anatomical and physiological limitations of the human auditory system, as well as by the physical construction of the HPD and its interface with the ear.

Sound paths for the occluded ear

The occluded (with an HPD) ear receives sound via four distinct sound pathways: (1) *air leaks* (generated when HPDs fail to form an airtight seal), (2) *HPD vibration* (due to the flexibility of the ear canal flesh or flesh around the ear), (3) *material transmission* (dependent upon the mass, stiffness, and internal damping of the HPD material), and (4) *bone conduction* (paths by which sound may bypass the HPD and reach the inner ear). These four pathways (Figure 2) establish functional limitations on HPD noise attenuation. More detailed discussion on these issues may be found in Berger (1986a) and Zwislocki (1957).

Occlusion effect

The "occlusion" effect is a physical phenomenon that results in auditory perception when the ear is occluded with an HPD. It occurs because the transmission efficiency of bone-conducted signals for low frequencies (below about 2 kHz) is enhanced relative to the unoccluded ear (Berger, 1980a, 1988a; Berger and Kerivan, 1983; Gorman, 1982; Tonndorf, 1972). An occlusion effect may be experienced whenever any type of HPD is donned, but is more pronounced when the ear canal is covered at its entrance with an ear canal cap or a shallow-fitting earplug (Berger, 1986a, 1988a). With large volume earmuffs or deeply-inserted earplugs, the

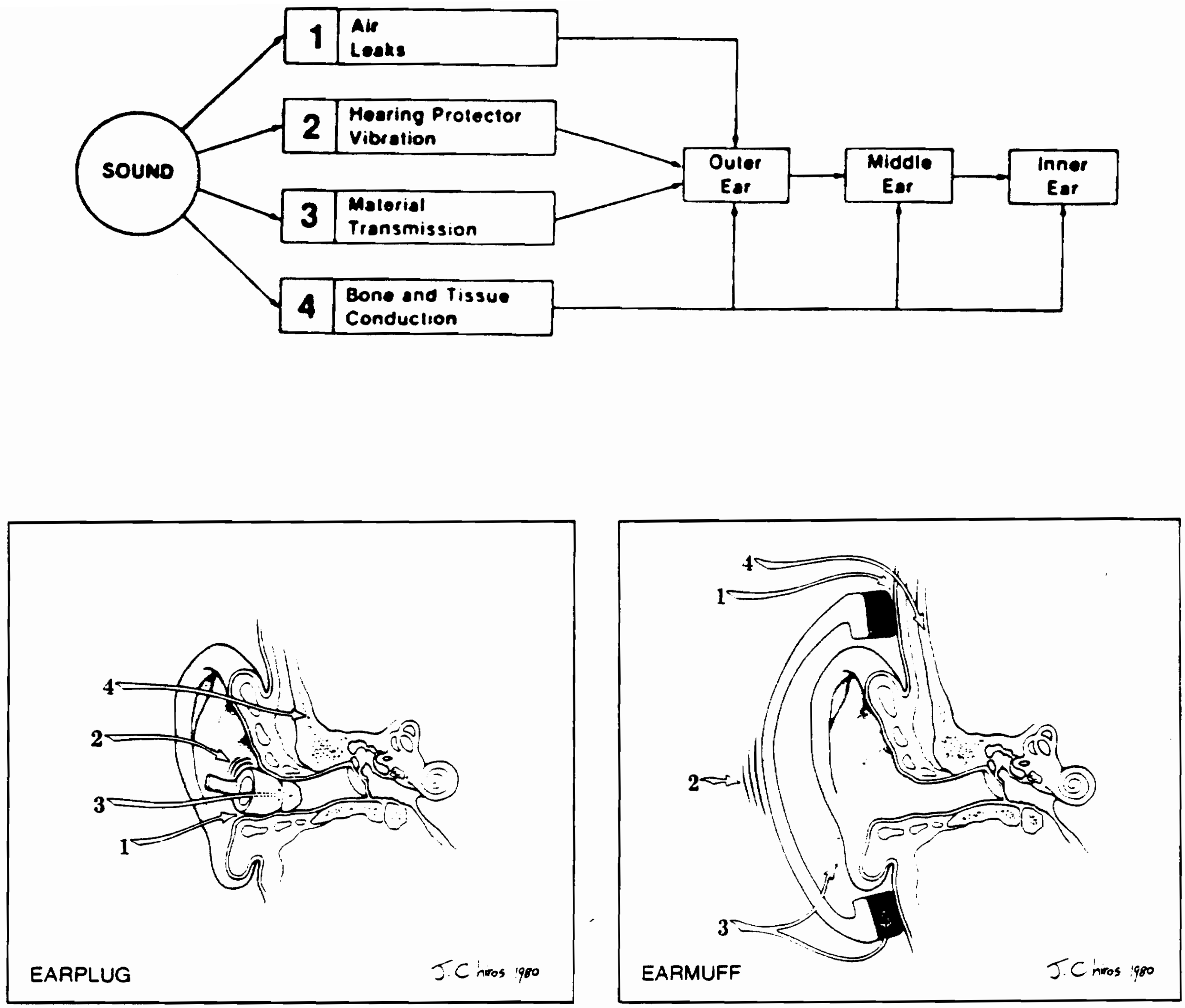

Figure 2. Sound paths for HPDs: (Berger, 1986a, pp. 321-322 - reproduced with permission).

occlusion effect diminishes. The occlusion effect may also result in an overestimation of HPD low frequency attenuation, because of raising of the occluded threshold by masking due to the physiological noise effects (e.g., the sound of blood flowing, heartbeat, and breathing) which are amplified under the protector. The overestimation may be up to 5 dB (Berger and Kerivan, 1983) or 6 dB (Anderson and Whittle, 1971), causing rather significant inflation of the protector's apparent performance below 2 kHz.

Noise Attenuation

According to Berger (1986b), HPD noise attenuation can be more accurately defined in terms of "insertion loss" and "noise reduction," since attenuation itself is not a precisely defined acoustical term. Insertion loss is the difference between the two sound pressure levels (SPLs) in dB measured at the reference point (i.e., in the ear canal) before and after a specific HPD is donned. Insertion loss can be measured either psychophsically (subjectively) or physically (objectively), as discussed later in the "METHODS FOR MEASUREMENT OF HPD ATTENUATION" section. Noise reduction, on the other hand, is a direct measure of the noise reduction achieved, obtained by subtracting the SPL at the reference point (i.e., inside the HPD) from the SPL at the transmitting point (i.e., outside the HPD). Thus, noise reduction is measured by physical methods, such as the "Microphone in ear" procedure (to be explained). More often than not, insertion loss offers a more accurate HPD attenuation measurement than does noise reduction, for the reduction in SPLs at the listener's eardrum is typically the preferred objective.

For the purpose of this dissertation, the term "attenuation" is defined as "the difference in occluded and unoccluded hearing thresholds, obtained psychophysically, for the given HPD." In this sense, a psychophysical measure of insertion loss is obtained for the HPD in question, using the ear's sensitivity as the indicator of SPL under the protector.

Factors Influencing Field HPD Performance

Several factors can compromise HPD performance in the workplace. Such factors include field activity movement, device wearing time, HPD fitting instruction, comfort provided by the HPD, HPD deterioration, HPD misuse, and HPD abuse.

Activity movement and wearing time

An HPD wearer's movement in the workplace is probably one of the major contributors to reduced HPD attenuation. For instance, head and jaw movements have been said to loosen earplugs and earcaps from the ear canal and break the earmuff cushion seal against the head, resulting in reduced noise attenuation (Abel and Rokas, 1986; Berger, 1981b; Kasden and D'Aniello, 1976; Waugh, 1983). A few research studies have addressed this issue.

Using 23 subjects and narrow band test stimuli whose center frequencies varied in one-octave intervals at 250, 500, 1000, 2000, and 4000 Hz, Cluff (1989) evaluated 3 different user-molded slow-recovery foam earplugs and 2 premolded earplugs (one poly-flanged and one glass fiber) to compare changes in attenuation after 30 minutes of controlled jaw movement. For the jaw movement task, each subject chewed gum at a rate of one jaw stroke per second for 30 minutes. The results showed that the changes in attenuation (across frequency) from before to after the jaw movement condition caused by the 5 earplugs were statistically significant

($p < 0.01$). The magnitude of difference for each HPD was the E-A-R plug by +0.9 dB, the Pura-Foam by +0.1 dB, the 3M-6300 by -2.0 dB, the Com-fit by -4.0 dB, and the Bilsom Soft by -8.1 dB. The improvements in attenuation for 2 of the expandable, slow-recovery foam plugs (i.e., the E-A-R and the Pura-Foam) give rise to the suspicion that expansion time (which is necessary for slow-recovery plugs) before the pre-chewing protected-threshold tests was insufficient. However, there was no report concerning the expansion period used. The author concluded that the expandable, slow-recovery foam plugs were more stable than other types of earplugs. In particular, the most and the least stable earplugs were the E-A-R and the Bilsom Soft plugs, respectively.

Recently, a laboratory study (Grenell, 1988) was performed at Virginia Tech to investigate the influence of user activity movement and various earmuff design variables, such as headband compression force and earcup cushion material, on the frequency-specific noise attenuation achieved with earmuffs. A work task, which simulated movements required in a light industrial assembly task performed at a sit-stand workstation, was devised for accomplishing controlled and time-paced head and body movements. Statistical analyses showed that activity movements significantly reduced the achieved earmuff attenuation, but only at 125 Hz. A high headband compression force was found to increase earmuff attenuation, while no significant difference was indicated between the 2 cushion materials (liquid- and foam-filled).

More recently, a controlled laboratory simulation study (Park, 1989) was conducted at Virginia Tech (as a master's thesis) to determine the effects of HPD wearing time, subject activity movement, and HPD fitting procedure on the spectral noise attenuation and user comfort achieved with various HPDs. Almost no differences in achieved attenuation or comfort were indicated between jaw and work activity movements. Also, the foam earplug was found to be most resilient to either type of activity movement, whereas the earmuff tended to slip during highly kinematic work activity movement. More discussion on this study appears in the forthcoming "LABORATORY-BASED PREDECESSOR STUDY TO THE CURRENT STUDY" section.

HPD placement on the wearer may change over time. As the wearer moves, talks, works, eats, or perspires, the noise-blocking seal may loosen. Occasional manual adjustment of the HPD may be required to maintain proper protection. The effect of wearing time on HPD attenuation has been investigated by a few researchers (e.g., Abel and Rokas, 1986; Berger, 1981b; Kasden and D'Aniello, 1976; Krutt and Mazor, 1980). A detailed review of these studies may be found in Park (1989).

From the aforementioned studies concerning wearing time effects and the recent thesis of Park (1989), the following general conclusions can be drawn. First, the attenuation of certain premolded earplugs and earmuffs may decrease over certain wearing periods, e.g., of one hour or longer. Second, in the case of expandable, slow-recovery foam plugs (e.g., the E-A-R plug), the results have yielded a few discrepancies. That is, the foam plug in the Abel and Rokas (1986) study provided a slight decrease in attenuation over time, while the foam plug investigated by Krutt and Mazor (1980) consistently improved its attenuation over wearing periods. This discrepancy raises an important issue on the fitting time for the slow-recovery foam plug. A possible explanation of the improvement of attenuation in the Krutt and Mazor (1980) study is that insufficient earplug expansion time was given prior to the initial attenuation testing so that plugs were not fully expanded before the first attenuation test (Berger, 1981b). The most recent study (Casali and Park, 1990b) verified that with sufficient fitting time (e.g., at least 2 - 3 minutes) foam plugs do not change their attenuation over the course of a wearing period, even if highly kinematic activity is involved.

HPD fitting instruction

Industrial workers are often not instructed or are improperly trained in HPD donning procedures. Effective application/fitting techniques are critical to achieving adequate HPD attenuation.

Casali and Epps (1986) evaluated the sound attenuation achieved with 5 common earplugs under 5 different instruction techniques (no instruction, manufacturer's package instructions, insertion using noise feedback, detailed written instructions, and interactive instructions from an experimenter), using 5 groups of 10 subjects, with each group receiving 1 level of instruction. The results indicated that insertion-instruction strategies significantly influenced the attenuation level, with more detailed and interactive instructions providing the best fit.

In the follow-up study (Casali and Lam, 1986a) using a similar experimental protocol, 4 earmuffs and 2 earcaps were investigated instead of earplugs. The attenuation results revealed that earmuffs and earcaps, as a group, were less susceptible than earplugs to changes in user instruction technique. It was also demonstrated that with any instruction at all, the achieved attenuation of the HPDs was significantly improved over the no-instruction condition.

Casali and Park (1990a) also showed that training to achieve better HPD fitting can noticeably improve noise protection, especially for the earplugs (e.g., the E-A-R plug). The earmuff was found to be not sensitive to the fitting effect, as corroborated by Casali and Lam (1986a). More detail on the Casali and Park (1990a) study will follow.

HPD comfort

"The best HPD is the one that workers will wear." This adage simply purports that comfort is probably one of the most important factors determining HPD effectiveness. HPDs must be comfortable enough so that workers can wear them properly for extended periods. In reality, workers often adjust and/or modify HPDs for comfort, rather than for achieving maximum attenuation (Wilson, Solanky, and Gage, 1981). They may even doff and don the devices repeatedly if the HPDs are uncomfortable, as evidenced in a survey by Royster and Holder (1982). Unfortunately, such actions to increase comfort will result in a decrease in time-weighted noise protection. This result has been demonstrated by Berger (1980a) using the data illustrated in Figure 3. For example, if an HPD with the Noise Reduction Rating (NRR) of 25 dB is not worn for only 15 minutes out of an 8-hour work shift in noise, then the resultant "Time Corrected NRR" will be 20 dB. In other words, even a 3% non-wearing time will result in a 20 percent reduction of time-weighted protection. More drastic reduction of protection will result as HPD wearing time decreases. Therefore, in a practical sense, HPD comfort is a critical factor in determining HPD effectiveness in the workplace.

In general, more comfortable HPDs do not necessarily fit better (Berger, 1982a), nor do they provide the best attenuation. It is critical not only that the selected HPDs provide adequate attenuation for the offending noise environment, but also that the devices are comfortable and acceptable to the workers, as well. Therefore, attenuation and comfort must both be considered when selecting an HPD.

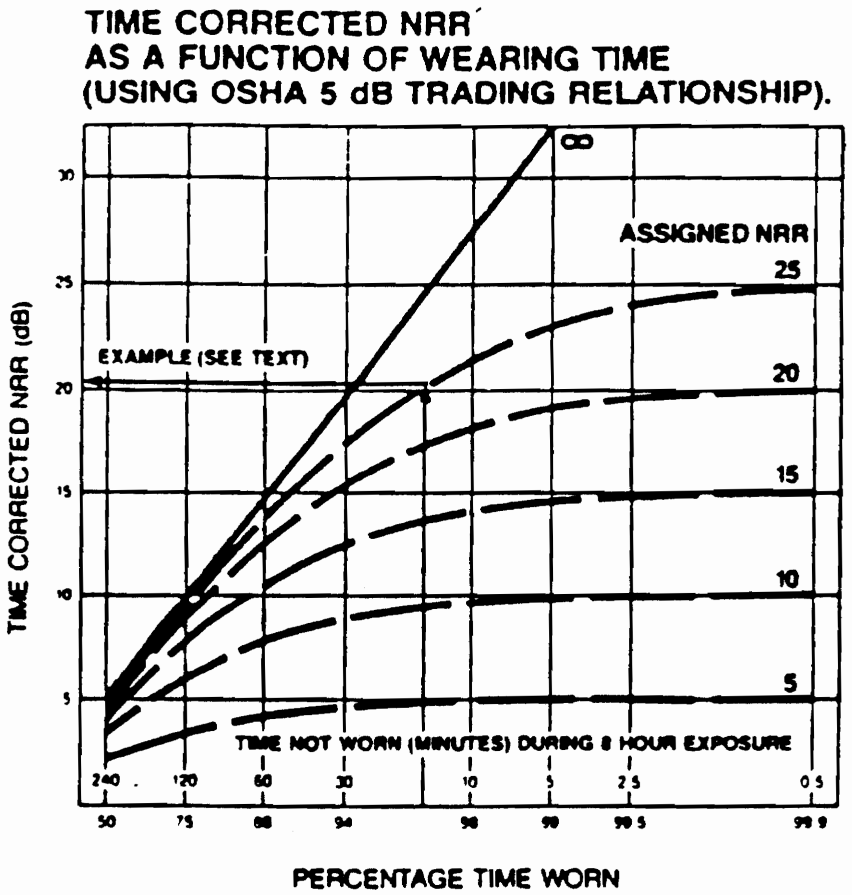

Figure 3. Protection versus percentage time worn: (Berger, 1980a, p. 17 - reproduced with permission).

HPD deterioration

HPDs should be able to survive durability tests, such as strain tests, drop tests, and humidity and temperature tests (Brinkman and Serra, 1982). The materials (e.g., plasticizers and foams) of many HPDs deteriorate over time. Hard use over long periods of time requires a durable HPD or, alternatively, one which is inexpensive and disposable. A worn-out or damaged HPD will not provide optimal protection for the worker. Therefore, a periodic maintenance/replacement plan should be part of the overall HPD hearing conservation program.

HPD misuse

HPDs in the workplace are often worn improperly due to factors such as discomfort, inadequate employee motivation and training, and so on. Earplugs are often not inserted deeply enough, and thus do not properly seal the ear canal. Also, many workers do not appropriately straighten their ear canals, by pulling the pinna upward and outward, prior to insertion (Riko and Alberti, 1982). Particularly with expandable foam plugs, workers may fail to roll the plugs small enough and insert them quickly enough to obtain a sufficiently deep insertion before they expand.

Common problems associated with earmuffs and earcaps include proper placement and orientation of the earcups (for earmuffs) and pods (for earcaps), wearing earmuffs/earcaps over hats and glasses, and failure to pull interfering long hair from beneath the sealing cushion (Riko and Alberti, 1982; Wilson et al., 1981). Also, the user should realize that the different headband orientations (i.e., over the head, behind the head, or under the chin) will typically result in different amounts of attenuation.

Berger (1988a) provides a comprehensive set of tips for proper fitting of different types of HPDs.

HPD abuse

Workers sometimes intentionally alter (abuse) the HPD for a variety of reasons. Berger (1980a), Gasaway (1984), and Riko and Alberti (1982) all indicate that discomfort and communication difficulty are the main reasons for worker modification of HPDs. Of course, modification of HPDs, such as trimming the flanges on rubber earplugs or "reverse-bending" the headband on earmuffs to relieve compression, usually results in a reduction of attenuation.

METHODS FOR MEASUREMENT OF HPD ATTENUATION

Over the past few decades, numerous HPD attenuation measurement methods have been proposed, devised, and a few have been empirically tested. These methods may be broadly categorized into subjective and objective procedures. Although excellent and thorough reviews on these methods are presented in Berger (1986b) and Nixon (1982), this section will briefly review the most widely accepted existing measurement methodologies for determining field HPD attenuation under the two categories of subjective and objective methods.

Subjective Methods

Subjective (or psychophysical) approaches mainly rely on a human subject's responses to auditory stimuli presented under protected (occluded with an HPD) and unprotected (unoccluded) conditions. (Although such methods have been historically termed "subjective" in the acoustical literature, this is probably not the most appropriate term from a behavioral science standpoint because subjective usually connotes "of subjects' judgment or opinion" in a human factors sense. For this dissertation, both terms, "subjective" and "psychophysical," are used synonymously.) Under each condition (protected or unprotected) in the subjective procedures, a psychophysical method is typically applied to determine the subject's hearing thresholds. An example would be the method of limits (Gescheider, 1985) in which a tone of certain frequency is presented to the subject in a series of alternate ascending intensity (in dB) and descending intensity trials, with the intensity level under experimenter control. The subject's absolute threshold is then determined by the average of dB hearing level (dBHL) responses across all ascending and descending trials. The arithmetic difference in the subject's threshold responses (protected threshold minus unprotected threshold) is taken as a measure of the HPD attenuation.

Two important methods for field HPD attenuation measurement are "real-ear attenuation at threshold" (REAT) and "above threshold" (AT) procedures.

REAT methods

REAT methods are the absolute threshold shift techniques. They are probably the oldest and, certainly, the most common and widely accepted methods of measuring HPD attenuation (Berger, 1986b). Many countries, including the U.S.A, Canada, West Germany, United Kingdom, and Australia, have adopted REAT methods in national testing standards (e.g., ANSI S3.19-1974, ANSI S12.6-1984, BSI 5108). Due to their significance in practice, REAT methods will be discussed separately later in this section.

Above threshold (AT) methods

AT methods offer investigation of three broad aspects: the possibility of sound level-dependent attenuation effects, REAT errors from masking effects due to physiological noise, and additional measurement methods to evaluate field HPD performance. AT procedures can generally eliminate the need for expensive test chambers (Berger, 1986b), but have other disadvantages. Two different AT procedures include "midline lateralization" and "temporary threshold shift."

Midline lateralization

Lateralization describes the sensation which arises when headphone-presented acoustic stimuli appear to emanate inside the head (Berger, 1986b). Sounds with similar intensity and pitch, which are presented to the two ears, are said to be midline lateralized if the lateralized location is the middle of the head. The HPD attenuation is the difference between the sound pressure levels in the test ear of the two conditions (with or without an HPD) when subjects perform the midline lateralization (ML) at the same position in the head. The ML method, which was introduced to evaluate insert-type HPD performance in the real-world, did show a good agreement with the REAT procedure using headphones (Fleming and Cudworth, 1979, cited in Berger, 1986b). However, the ML has not been widely applied for real-world situations due to the difficulty in equipment availability and test procedures in the workplace (Berger, 1986b).

Temporary threshold shift

The temporary threshold shift (TTS) method bases the attenuation characteristics of an HPD on the change in an open-ear threshold before and after the subject is exposed to high-level noise while wearing the HPD (Nixon, 1982). Attenuation of an HPD is then based on the ability to reduce TTS. Thus, the TTS provides qualitative estimates of the differences in the degree of protection among the HPDs tested. The TTS method is reported (Royster, 1980) to be especially useful for evaluation of field HPD performance. Thus, it is a valuable tool for determining the effectiveness of hearing conservation programs. However, it does not provide quantitative, frequency-specific measure of the actual attenuation of an HPD and thus is not useful for matching HPDs to specific noise problems.

Other subjective (i.e., psychophysical) methods for measuring HPD attenuation include "loudness balance," "masked-threshold," and "cross-modality matching." Due to the low significance of their application in real-world environments, these methods are not discussed here. For more details on these procedures, the reader is referred to Berger (1986b) and Nixon (1982).

Objective Methods

Objective HPD attenuation measurement procedures use transducers (miniature microphones) in artificial or human heads. Data are measured directly from sound level meters, without reliance on human judgment, and the acoustical quantity measured may be either insertion loss or noise reduction (defined previously in the "Noise Attenuation" section), depending on how the test is conducted. Unfortunately, these objective procedures do not consider the effects of natural human variability on the protection values obtained, nor do they account for bone conduction effects which theoretically limit the attenuation to be obtained.

Currently available objective methods include "microphone in real ear," "microphone in cadaver ear," "acoustical test fixture," and "aural reflex." Only the microphone in real ear method will be discussed here due to its feasibility for real-world HPD research. The reader is referred to Berger (1986b) for information on other objective methods.

Microphone in real ear (MRE)

Modern technological innovations (i.e., audio-dosimeter and miniature microphones) gave birth to the MRE method. Attenuation of an HPD is measured by positioning one microphone (for insertion loss) in a human ear with and without the HPD donned, or two microphones (for noise reduction), one underneath and one outside the HPD.

Several authors, including Berger and Kerivan (1983), have compared this method with other subjective methods, such as REAT. Such efforts have revealed that this technique has been limited to measuring circumaural and supra-aural HPDs, but not insert-type HPDs, due to the difficulty of mounting a microphone in the ear canal in conjunction with the insertion of an earplug into the same canal.

Despite some drawbacks, including the neglection of including bone conduction path effects, the MRE procedure offers the advantage of a more accurate test fixture that accounts for all of the human anthropometric features and leakage paths (Berger, 1986b). For this reason this method is expected to be even more common for field use in the future, though the microphone, wiring, and associated apparatus may be intrusive to the worker's job performance.

REAT and HPD Testing Standards

REAT method

Two general methods of implementing REAT classified by Berger (1984, 1986b) are sound field REAT and headphone REAT.

The sound field REAT method utilizes a sound field generated in a test booth using loudspeaker-presentation of test signals. Research using the sound field REAT procedure has been conducted on several different issues which are thought to influence the results, such as ambient noise (Waugh, 1970), stimulus bandwidth

(Waugh, 1974; Webster, Thompson, and Beitscher, 1956), and physiological noise (Berger and Kerivan, 1983).

High ambient noise levels tend to mask (hence elevate) the open ear thresholds, ultimately resulting in lower attenuation values caused by the reduced threshold shift between occluded and unoccluded trials. Waugh (1970) demonstrated this effect for two earmuffs by experimentally determining the levels of ambient noise that would mask low-frequency open ear threshold levels by 3.5, 7.5, and 11.5 dB, averaged across 11 test frequencies ranging from 100 to 1000 Hz. Octave band ambient noise levels ranged from 10 dB at 1000 Hz (for the 3.5 dB masker) to 40.5 dB at 125 Hz (for the 11.5 dB masker). The results showed that as the masking level increased, the resultant earmuff attenuation decreased accordingly.

Webster et al. (1956) compared REAT results using pure-tone, one-half octave band, and one octave band stimuli. They concluded that the use of noise bands or pure-tones did not yield significantly different attenuation results for the HPDs. Waugh (1974) also compared REAT results for pure-tone and one-third octave band stimuli. A similar conclusion (i.e., insignificant influences of test stimuli on HPD attenuation) to that of Webster et al. (1956) was drawn. He, however, demonstrated that small (but statistically significant) errors will arise when an HPD's attenuation for a particular octave band noise is assumed to be identical to the attenuation for pure-tone or one-third octave band stimuli centered within that octave band.

Turning to physiological noise (e.g., heartbeat, blood flow, and other internal noises), Berger and Kerivan (1983) experimentally verified the exact relationship of physiological noise to threshold testing of HPD attenuation. They found that the occlusion effect, the degree of amplification of physiological noise, and the amount by which the REAT values were amplified, were all dependent upon the occluded volume formed by the HPD.

Despite its requirement of a specific test space with low ambient noise levels, the sound field REAT is acoustically one of the most accurate methods. It is applicable to all types of linear HPDs (devices providing constant attenuation over all sound levels), but not to the less common amplitude-sensitive or level-dependent HPDs (devices having electronic circuitry, valves, or other means of increasing attenuation with high sound levels but passing signals otherwise). The former variety of HPD is by far the most common for industrial applications.

Headphone REAT, implemented by Padilla (1976), uses test signals presented through small loudspeakers inside a set of headphones. This method greatly simplifies the test equipment required, eliminates sound field calibration, and reduces background noise problems, thus it is good for field application. A similar headphone REAT method, named the EAL (Environmental Acoustics Laboratory) field method, resulted from a NIOSH-funded study (Michael, Kerlin, Bienvenue, Prout, and Shampan, 1976) for field earplug evaluation. This simple method provides a means of correcting (using linear equations) attenuation measurements obtained in the workplace to attenuation values that would have been obtained if the ANSI S3.19-1974 standard methodology had been used. The EAL method was not intended to replace the ANSI S3.19-1974 standard, but rather to simplify the field attenuation measurement scheme.

One major problem with both headphone and sound-field REAT methods, as indicated by Anderson and Whittle (1971), Berger and Kerivan (1983), and Rudmose (1982), is the masking of occluded ear thresholds by the presence of physiological noise. This physiological noise is usually vascular and/or muscular in nature (Anderson and Whittle, 1971) and is primarily a low-frequency (below 1000 Hz) phenomenon. As previously discussed, physiological noise is amplified due to the occlusion effect when the ear is covered with the HPD, thus causing an overestimation of the low frequency attenuation of HPDs.

The sound pressure linearity assumption (i.e., HPD attenuation does not change over the range of sound pressure levels) associated with REAT procedures has been verified by several researchers (e.g., Berger and Kerivan, 1983; Martin, 1982). The results of those studies supported the fact that the REAT results obtained at low sound levels are applicable to high level noise environments where the HPDs will be used.

ANSI HPD testing standards

The REAT (Real-Ear Attenuation at Threshold) method, which is based on psychophysical testing procedures, was adopted by ANSI (American National Standards Institute) in 1957 (ANSI Z24.22), 1974 (ANSI S3.19 - the test standard currently matched and specified in the EPA [1990] labeling regulation), and in the most recent standard (ANSI S12.6-1984). Primary revisions in the more recent standards include sound field characteristics in the test chamber (although the differences between S3.19-1974 and S12.6-1984 are small in this regard) and procedures for fitting the HPD on the subject. A tabular comparison of the above 3 standards appears in Berger (1985).

The ANSI S12.6-1984 standard, "Method for Measurement of Real-Ear Attenuation of Hearing Protectors," and its predecessor, ANSI S3.19-1974, are intended to yield optimum performance data which may not usually be obtained under field conditions. The standard requires pulsed one-third octave band test noises, centered at 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz, to be presented in a sound field which provides uniform test noise levels about the seated subject's head. HPD fit in the 1984 protocol is achieved by the subjects themselves, but under the experimenter's supervision. After fit is established, further adjustment of the HPD is not permitted during testing.

A psychophysical procedure, such as the method of limits (experimenter control of levels) or the method of adjustment (subject control of levels) (Coren, Porac, and Ward, 1984; Gescheider, 1985), is used for REAT testing to determine subjects' occluded and unoccluded thresholds. Both manual audiometry or automatic Békésy audiometry (Békésy, 1960; Hallpike, 1976) may be used to establish the thresholds. Three thresholds are required under both occluded and unoccluded ear conditions at each test frequency. For each occluded/unoccluded threshold pair, the difference between threshold values in dB is taken as one observation of the attenuation of the HPD at that frequency. At least 30 such attenuation observations (3 for each of a minimum of 10 subjects) are required for computation of the Noise Reduction Rating (NRR), currently required by the Environmental Protection Agency (EPA) for all HPDs (EPA, 1990). Attenuation tests for the current research were conducted in strict accordance with the ANSI S12.6-1984 standard, with respect to all electro-acoustic requirements. However, some modifications in test protocols (e.g., HPD fitting conditions) were employed as needed to examine the variables of experimental interest.

RATING HPD ATTENUATION

A single-number rating of HPD attenuation has the advantage that it can be subtracted from an appropriate sound level measurement of the noise environment, thus providing a simple estimation of the wearer's protected noise exposure. Spectral attenuation data (i.e., means and standard deviations of attenuation at the 9 frequencies) resulting from the REAT tests (as per ANSI S12.6-1984 standard) can be converted to a single-number measure of HPD attenuation using the EPA Noise Reduction Rating (EPA, 1979, 1990). Distillation of these spectral data to a single broadband rating affords a simple, convenient means for comparing and selecting HPDs, although it is not a substitute for the frequency-specific information.

Noise Reduction Rating (NRR)

The Noise Reduction Rating (NRR) is currently the most common single-number HPD attenuation measure. According to the EPA (1990), it is required as a part of the label on all HPD packages produced after September 27, 1980 (Michael, 1982).

The NRR is the difference between the overall C-weighted sound level of a pink (flat by octaves) noise spectrum and the A-weighted noise levels reaching the wearer's ear with an HPD donned. An example NRR calculation is presented in Table 1. A 2σ correction in the NRR calculation indicates that the attenuation values used in the computation are theoretically obtainable by 98 percent of the wearers with correctly worn HPDs. A 3 dB spectral uncertainty correction in step 9 of Table 1 is to protect against overestimating the HPD attenuation as a result of potential

Table 1. An Example of the NRR Calculation for HPD Attenuation

(Berger, 1986a, p. 329 - reproduced with permission; * Correction from original)

Octave Band Center Frequency (Hz)	125	250	500	1000	2000	4000	8000	dB(X)[A]
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. Typical premolded earplug attenuation	27.4	26.6	27.5	27.0	32.0	46.0[B]	44.2[C]	
7. Standard deviation × 2	7.8	8.4	9.4	6.8	8.8	7.3[B]	12.8[C]	
8. Estimated protected A-weighted sound levels [step 5 - step 6 + step 7]	64.3	73.2	78.7	79.8	78.0	62.3	67.5	84.2 [dBA]

9. NRR = step 3 - step 8 - 3[D]
NRR = 107.9* - 84.2 - 3 = 20.7 dB

The NRR represents the attenuation that will be obtained by 98% of the users in typical industrial noise environments, assuming they wear the device in the same manner as did the test subjects, and assuming they are accurately represented by the test subjects.

[A] Logarithmic sum of 7 octave band levels in the row. This is a C-weighted sound level for step 3 and an A-weighted sound level for step 8. See Chapter 2 for method of computation.

[B] Arithmetic average of 3150 and 4000 Hz data.

[C] Arithmetic average of 6300 and 8000 Hz data.

[D] The 3-dB spectral uncertainty factor is to protect against overestimates of the HPD's noise reduction that could arise from potential differences between the assumed spectrum and that of the user's actual exposure.

differences between the assumed C-weighted pink noise spectrum and that of the wearer's actual exposure. In practice, the NRR is used to estimate wearer noise exposure (in dBA) by subtracting it from the C-weighted workplace noise level.

Field NRR

A field noise reduction rating, termed RW NRR_{84} (real-world NRR_{84}, or in this dissertation, field NRR_{84}), was suggested by Berger (1983) on the basis of a compilation of data from 10 field and laboratory studies for the real-world performance of the HPDs. The RW NRR_{84}, a modified NRR (with 1 σ correction, rather than 2 σ as in the original NRR), is a prediction measure of the minimum protection that 84 percent of the HPD wearers achieve, rather than 98 percent as in the original NRR, or NRR_{98}. The 1 σ correction is considered more appropriate (i.e., realistic) for field application. A comparison of the NRR (i.e., NRR_{98}) and the RW NRR_{84} for both earplugs and earmuffs, presented by Berger (1983), shows that the RW NRR_{84} value is considerably smaller (i.e., less than half) than the labeled NRR (i.e., NRR_{98}) value.

As an alternative way to estimate field NRR, Berger (1983, 1986a) also suggests a derating scheme, e.g., a reduction of the NRR by 10 dB before subtracting it from the measured C-weighted workplace noise level. This derating of laboratory data is justified by the fact that laboratory data do not correctly represent the values attained by actual users due to the different underlying conditions between laboratory and field environments, thus resulting in inflated NRRs.

HPD PERFORMANCE IN THE FIELD

As indicated earlier, it has been clearly found, through empirical research, that field performance of HPDs is considerably less than optimally estimated by laboratory methods. This discrepancy is due mainly to ideal laboratory conditions. That is, laboratory subjects are well-motivated, trained, and under close experimenter supervision; laboratory tests are conducted using properly fitted new HPDs worn in a short wearing period, etc. Furthermore, in the industrial field, active workers move, talk, and even adjust or refit their HPDs during long wearing periods. Thus, laboratory-obtained, manufacturer-supplied data usually overestimate the performance of the HPDs to be used in the field. When the laboratory-obtained attenuation values are strictly relied upon, this poses the threat of underprotection for the worker against hazardous high-intensity noise in industrial environments.

Some prior research has been conducted, either to simulate field performance of HPDs in the laboratory settings, or to evaluate HPD performance in the actual field settings. Due to the field focus of the current study, the following section reviews research on the latter in two separate categories: field HPD attenuation and field HPD comfort. An exhaustive review on the laboratory simulation of field HPD performance (both attenuation and comfort) appears elsewhere in Park (1989).

Field Assessment of Actual HPD Attenuation

Several studies have been conducted to assess actual field HPD attenuation. In each study, measurement facilities were located at or near the work sites either in a mobile unit or in a quiet chamber inside the plant. The workers, who were aware that they would be subjects for the experiment but not aware of the exact times of their tests, were instructed to go (or were escorted) to the test facility directly from their workplace, while wearing their HPDs as found on the job. They were carefully monitored to assure that they did not readjust their HPDs until the end of the attenuation testing, so that protection levels for the HPDs as found fit by the workers were established.

Regan (1978), based on his doctoral dissertation in 1975, was the first investigator to measure the attenuation of HPDs as worn by employees in industry. The attenuation data for 3 earplugs and 1 earmuff (manufacturers and model names not reported) were collected on 32 male workers working in a steel stamping plant. Psychophysical testing was conducted at 4 random times during a 2-week period, using the ANSI Z24.22-1957 standard with 7 pure-tone test frequencies in octave steps from 125 to 8000 Hz in a free-field audiometric van. The results indicated that all HPDs performed significantly poorer than manufacturers' published attenuation. The best field performance was achieved by the malleable sponge (foam) earplug, followed in descending order by the earmuff, the non-malleable rubber earplug, and the custom-molded earplug.

Using a headphone REAT method (i.e., using a modified set of large circumaural earmuffs fitted with earphone loudspeakers) in a van, Padilla (1976) investigated 2 types of earplugs: standard V51-R and custom-molded plugs. The selected industrial workers were tested using only a 500 Hz pure-tone signal, which was simultaneously directed to both ears. As stated by the author (Padilla, 1976, p. 34), "The tests were conducted only at 1 frequency (500 Hz) under the common knowledge that the real attenuation of an earplug tends to increase in frequency, so that if the attenuation was found acceptable at 500 Hz, it was assumed to also be acceptable at higher frequencies." (This is somewhat of a tenuous assumption, given the highly variable fit achieved by industrial personnel.) According to the results, 83% of workers who wore the V51-R received less than 20 dB of noise reduction; 36% were found to be completely unprotected. On the other hand, the custom-molded plug provided better protection: 66% received less than 20 dB, and only 2% demonstrated no protection. The results contradict those of Regan (1978), who found the custom-molded plug the poorest of 4 HPDs.

Using a similar headphone REAT procedure, called the NIOSH or EAL field method (Michael et al., 1976), several studies were conducted. Crawford and Nozza (1981) evaluated actual attenuation performances of 3 earplugs as worn by 87 workers in 4 manufacturing plants. Workers' hearing thresholds were measured at all test frequencies specified in ANSI S3.19-1974, except 125 Hz. According to the results, the premolded and the custom-molded earplugs performed the worst: the mean attenuations were less than 50% of the manufacturers' ratings, and standard deviations were 2 to 3 times greater than the manufacturers' values. The user-molded foam earplug, on the other hand, exhibited close mean attenuation values to those of the manufacturers' except at the low frequency end of the spectrum (i.e., 1000 Hz and below), but the variability was about the same as those of other earplugs.

Two large field HPD studies were conducted for NIOSH in 1977 (Edwards, Hauser, Moiseev, Broderson, and Green, 1978) and 1981 (Edwards, Broderson, Green, and Lempert, 1983). The field attenuation of 3 earplugs (premolded twin-flanged, premolded V51-R, and user-molded acoustic wool) were evaluated by Edwards et al. (1978). From each of 6 industrial plants, 28 workers were tested in an audiometric van at 5 random times over a period of 5 days. The results indicated that, on the average, workers were receiving noise protection ranging from 6 dB at 125 Hz to 20 dB at 3150 Hz, and that the average worker was realizing only 33 to 54% of the potential (i.e., manufacturer's rated) attenuation of the earplugs.

A larger-scale follow-up study (Edwards et al., 1983) investigated 3 additional types of earplugs (user-molded foam, custom-molded, and acoustic wool with a pre-formed shroud) and the same user-molded acoustic wool used in the first study. Using a similar experimental protocol, the study was conducted on 28 employees at each of 10 plants. The results revealed that average noise protection in the workplace ranged from 9 dB at 125 Hz to 29 dB at 3150 Hz, indicating protection levels well below those published by the manufacturers. Summarizing results from the 2 Edwards et al. field studies, Lempert and Edwards (1983) reported that 50% of the workers were receiving less than one-half of the protection levels published by the manufacturers.

Following the identical protocol used in the 2 previous Edwards et al. studies, Edwards and Green (1987) evaluated the field performance of the E-A-R foam earplug using 56 industrial workers at 2 DuPont plants, all of whom were participating in the company's hearing conservation program (HCP), which met or exceeded the 1983 Hearing Conservation Amendment (HCA) requirements. To determine the effectiveness of the HCP, the NRR_{84} results of 2 DuPont data (DuPont I and II, each corresponding to data from plants I and II, respectively) were compared to those of the NIOSH data (Edwards et al., 1983), which were collected prior to the existence of the HCA. The NIOSH data consisted of 4 separate sets, each resulting from each of the 4 industrial plants: NIOSH III and VIII (which used the E-A-R foam plug) and NIOSH VI and VII (which used the Decidamp plug). The computed NRR_{84} for DuPont I and II were 17.0 and 13.1 dB, respectively. Meanwhile, NRR_{84} values for NIOSH III, VIII, VI, and VII were 13.1, 9.9, 4.0, and 6.6 dB, respectively. Although the authors concluded that "workers participating in the HCP were receiving, on average, over 100 percent better protection, as established from a 6.8 dB increased NRR_{84}," this is a somewhat exaggerated conclusion based on an inappropriate comparison. That is, they compared the mean (i.e., 15.2 dB) of the 2 DuPont NRR_{84} data (achieved with only the E-A-R foam plug) to the mean (i.e., 8.4 dB) of all 4 NIOSH NRR_{84} values (provided by both the E-A-R foam and the Decidamp plugs). If the averaged NRR_{84} of the DuPont data had been compared correctly with the mean (i.e., 11.5 dB) of only 2 NIOSH data (III and VIII), which used the same E-A-R plug, the resultant difference due to the HCP would have been 3.7 dB, rather than 6.8 dB.

A comprehensive field study (Behar, 1985) was conducted at the Ontario Hydro power plant in Canada, using 3 earmuffs (including cap-mounted muffs), 3 earplugs, and 1 ear canal cap. The subject employees brought their own muffs, but plug and canal cap devices were supplied at the test site for attenuation tests performed as per a pseudo ANSI S3.19-1974 standard. That is, attenuation data were measured at the test frequencies specified in ANSI S3.19-1974, excluding 125, 3150, and 6300 Hz due to background noise problems and to shorten the testing time (Behar, 1985). NRR differences were found between the field and the manufacturers' ratings, ranging from 5 dB (for the SAFECO 204 earmuff) to 25 dB (for the E-A-R foam plug). Average overestimation was highest for the earplugs, followed by the canal cap (Willson Sound-Ban) and the earmuffs, in descending order. On the basis of the overall average NRR overestimation across the HPDs, Behar and Desormeaux (1986) suggested a minimum derating factor of 15 dB for realistic estimation of field attenuation performance from typical laboratory data.

Most recently, a field study (Pfeiffer, Kuhn, Specht, and Knipfer, 1989) was conducted in West Germany to evaluate the real-world performance of 3 earplugs and 4 earmuffs. Using a portable computer-controlled measurement system installed in a dual-cabin automobile, workers' hearing thresholds were measured in accordance with REAT procedures. The mean differences between field and laboratory attenuation values were 13.3 dB, 8.7 dB, and 5.9 dB for the E-A-R foam, Bilsom Soft, and Bilsom Propp-O-Plast earplugs, respectively. Earmuffs, on the other hand, yielded noticeably less field-laboratory differences; the mean differences ranged only from 2.3 to 5.7 dB.

Thanks to the recent advent of audio-dosimeter technology and miniature microphones, field earmuff attenuation can be measured physically using objective methods (e.g., microphone in real ear) without accounting for bone-conduction effects which bypass the tympanic membrane. Goff and Blank (1984) evaluated 5 different types of earmuffs under field conditions using 45 tests. The microphone in real ear (MRE) objective method (discussed previously under "Objective Methods") was used, i.e., tests were performed by recording sound levels simultaneously through one microphone placed inside the earmuff and a second microphone located outside the earmuff (i.e., on the shoulder). The results demonstrated that the actual noise protection measured in the field was again considerably less than the laboratory-estimated protection levels.

Another method for indirectly investigating actual field HPD noise attenuation is the TTS (temporary threshold shift) method, explained previously in the "Subjective Method" section. In other words, protection achieved by the HPD is estimated by measuring workers' hearing levels at the beginning and end of the workday to detect whether any TTS occurred in spite of protector use. Royster (1979) evaluated 3 earplugs worn by workers who were exposed to a TWA (time weighted average) of 95.5 dBA. The results indicated that TTS did not occur for the employees who wore the E-A-R foam plug. However, it did occur for the other 2 earplugs (Hear Guard and Sigma earplugs). In a similar study (Royster, 1980) conducted under a TWA of 95.6 dBA, the premolded V51-R plug was found to be associated with significantly more

TTS than the E-A-R foam plug. More recently, Royster, Royster, and Cecich (1984) compared the effectiveness of 3 HPDs at a synthetic textile plant under a noise level of 107 dBA TWA. In addition to TTS results, this study also provided results from the data base analysis approach to assessing overall HPD program effectiveness achieved in an industrial setting. Statistical analysis showed that the frequency-specific protection afforded by the E-A-R foam plug was significantly better than that of the other 2 HPDs: the Com-fit plug at 500-4000 Hz and the Silenta muff at 500, 3000, and 4000 Hz.

Although the E-A-R foam plug was reported to be superior to other HPDs from the Royster et al. studies, evidence from other field (e.g., Lempert and Edwards, 1983) and laboratory simulation (e.g., Casali and Park, 1990a) studies is in disagreement. These studies indicate that under field or simulated conditions, the E-A-R foam plug does not approach the attenuation levels reported on the packaging. This is due at least in part to the demonstrated tendency of the earplug to lose more of its reported attenuation under subject-fit conditions than some premolded or earmuff devices (Casali and Park, 1990a).

Collectively, prior field HPD studies indicate that the actual attenuation performance of HPDs in the workplace is considerably less than that of laboratory-obtained manufacturers' ratings. Therefore, relying on the manufacturers' on-package attenuation data, and hence overestimating actual noise attenuation afforded, poses a potential threat of underprotection for the noise-exposed workforce. To counteract this problem, new standard laboratory testing protocols need to be devised to yield more realistic estimates of HPD performance on which manufacturer ratings can be based. Furthermore, more effective industrial hearing conservation programs, including proper HPD selection, fitting, and user training/motivation, should help reduce the discrepancy between laboratory and field data.

Field Assessment of HPD Comfort

As discussed previously, HPD comfort is practically one of the most important factors which determine HPD effectiveness in the workplace. To date, noise attenuation has been a primary issue in HPD research, yet relatively less concern has been given to the comfort requirements of the user. A few studies, however, do warrant mention. This portion of the dissertation reviews the pertinent literature on HPD comfort and wearability investigated in field settings. A thorough review of laboratory comfort studies appears in Park (1989).

Ivergard and Nicholl (1976) evaluated both short-term (3-5 minutes) and long-term (over a half or full workday period) tests to develop a reliable and valid testing method for assessing earmuff comfort and wearability. Based on a five-point scale, 51 subjects rated 10 muffs in the short-term tests, while 24 people rated 4 muffs in the long-term tests. Finding significant rank correlation statistics between short-term and long-term ratings, the authors concluded that short-term impressions with an earmuff may well be a valid predictor of long-term comfort. However, the perception of earmuff weight was significantly different between short- and long-term tests; the same was true for the perception of cushion softness. Note that the idea of estimating long-term HPD comfort by short-term tests may not be appropriate for evaluation of certain HPDs, especially for ear canal caps, because these devices are known to become more uncomfortable with time.

An earmuff rating index was suggested by Lhuede (1980) as a method of earmuff selection. Achieved attenuation was multiplied by a "comfort factor," which was calculated as the inverse of the product of the clamping force and the weight of the earmuff. The higher the earmuff attenuation (achieved with heavier weight and higher clamping force), the lower the comfort factor, and thus, less user acceptability.

Twelve earmuffs selected on the proposed index were then tested using a five-point linear scale in a number of Australian mills. It was found that earmuffs with the highest (lowest) comfort indices were favorably (unfavorably) rated by workers. Most other comfort indexes could not be distinguished in terms of comfort or user acceptance of the muffs, thus leading to a general conclusion that comfort may not be judged adequately by using only two attributes of the muff.

Sweetland (1981) assessed comfort, convenience, and other wearability aspects (e.g., subjective pressure) of 8 earmuffs and 2 earplugs used by 27 coal miners. After wearing each protector for 5 workdays, the subjects completed a questionnaire containing several comfort-related scales. Several physical attributes of earmuffs, such as weight, headband force, and pressure, were also measured and associated with subjective assessments of comfort, convenience, and pressure. Earmuff mass was found to be highly correlated with comfort and perceived pressure. In addition, the ratio of mass to pressure resulted in significant correlations with comfort and perceived pressure.

Savich (1982) investigated the influence of the overall design and the application force of the seal against the head on earmuff comfort. Fourteen Canadian miners were asked to classify the comfort associated with 11 earmuffs on a simple rating scale of satisfactory, good, or very good. The results showed that larger cushion areas were significantly associated with greater comfort. It was also concluded that comfort and attenuation were interrelated and dependent on the headband compression force.

Using several earmuffs, earplugs, and ear canal caps, a comprehensive field study (Behar and Desormeaux, 1986) was conducted at the Ontario Hydro power plant in Canada. Employees brought their own muffs for both attenuation tests and comfort evaluation, while plugs and canal caps were supplied at the test site. The workers rated comfort of the devices based on a battery of 6 five-point scales. A single-number comfort index was computed by applying an unequal weighting scheme to scale items. That is, heavier weights were assigned to more important (as judged by the experimenter) scale items, and vice versa. The results showed that protectors with the highest comfort indexes were perceived as the most acceptable by the workers.

Recently, Mimpen (1987) performed an extensive field study of earmuff comfort on Dutch military personnel using 8 different earmuffs, all of which provided about equal noise attenuation (NRR = 28 dB). A questionnaire containing 18 five-point scales was used for the assessment of the perceived comfort. A total of 48 subjects, 16 at each of 3 locations (two shooting ranges and a workplace), wore 8 different muffs for one day each. The subjects rated each muff by means of the questionnaire at the end of each shooting or working day. The average score per earmuff was computed over the 18 scales and used for later data analysis. The statistical (parametric) results showed that the Peltor H7A muff was judged the most comfortable (by 60% of the subjects) and was significantly ($p < 0.01$) different from other muffs.

A multidimensional, bipolar adjective rating scheme was developed and validated by Casali et al. (1987) to assess and quantify subjective feelings of HPD comfort into a single-number rating, namely, the comfort index (CI). Subjects responded to a series of seven-point bipolar adjective scales based on the semantic differential scale developed by Osgood, Suci, and Tannenbaum (1978). Using different sets of bipolar rating scales and the CI concept, several laboratory comfort studies have been conducted at Virginia Tech (Casali and Grenell, 1990; Casali and Lam, 1986b; Epps and Casali, 1985). Refinement of these scales has since been performed, and the new scales were used in the laboratory study predecessor (Park,

1989) to the current field study. For comparison purposes between these two studies, the identical rating scheme was used (Park and Casali, 1991) in this field study.

LABORATORY-BASED PREDECESSOR STUDY TO THE CURRENT FIELD STUDY

Constituting the first phase of a NIOSH-funded 2-year project, a laboratory-based study (Park, 1989) was conducted in the Auditory Systems Laboratory at Virginia Tech as a precursor to the field study described in this dissertation. Comprising protocols to simulate certain field influences, the laboratory study investigated the effects of HPD wearing time, subject activity movement, and HPD fitting procedure on the frequency-specific attenuation and user-rated comfort achieved with a popular foam cushion muff (Bilsom UF-1), 2 common earplugs (a user-molded E-A-R foam and premolded, triple-flanged UltraFit plugs), and a muff over foam plug combination. Both attenuation and comfort data were collected from 40 naive but audiometrically normal subjects (10 on each device). Although its major findings are reported elsewhere (Casali and Park, 1990a; Park and Casali, 1991), due to its relevance to the current field study, a brief overview follows.

Using a psychophysical REAT measurement procedure (as per ANSI S12.6-1984 in a computer-controlled facility described in Casali, 1988), attenuation data were obtained before, during (following 1 hour of HPD wearing), and after (following 2 hours of HPD wearing) the activity movement tasks, which induced typical worker movements. To investigate activity movement and wearing time effects, 2 paced movement tasks were devised: temporomandibular "jaw movement," in which subjects alternated 5-minute intervals of reading aloud with 5-minute intervals of chewing gum or eating a snack over a 30-minute period, and a physical "work activity," in which subjects performed 6 highly kinematic standing work tasks using a Baltimore Therapeutic Equipment Work Simulator, combined with rapid head turning to monitor 2 rearward displays, over a 30-minute period. Each movement task (jaw or work activity) was performed for 2 30-minute bouts within a 2-hour HPD wearing period.

For each subject in each movement condition, fitting of the single assigned HPD was accomplished under 1 of 2 conditions: "subject-fit" and "trained-fit," with the trained-fit condition always preceded by the subject-fit condition. Once fit, the subject did not readjust the HPD over the full 2-hour wearing period. In subject-fit, the subject donned the HPD after viewing only the manufacturer's printed instructions, without any assistance from the experimenter. In trained-fit, the subject practiced donning the HPD after reading the manufacturer's instructions and while receiving verbal guidance and close supervision from the experimenter. These 2 identical fitting procedures were also used in the current field study.

Bipolar comfort rating data were also collected before (15 minutes after initial fit of the HPD) and after (following 2 hours of continuous HPD wearing) the activity movement tasks, using 7-step bipolar adjective rating scales.

The results of statistical analyses indicated that achieved attenuation and user comfort significantly decreased over the 2-hour wearing period and that training (to achieve better fitting) markedly improved the noise protection, although these changes were device- and frequency-specific. Loss in frequency-specific attenuation over the activity period was up to 6.3 dB for all HPDs except the foam plug, and attenuation improvement due to user training ranged from 4 to 14 dB for all HPDs except the earmuff at 1000 Hz and below. There was no training effect on the achieved earmuff attenuation. Although a trend showed that perceived comfort degraded significantly over the wearing period, the earplugs provided consistent comfort. However, comfort provided by both earplug devices was sensitive to the fitting effect, whereas the earmuff configuration did not show any significant differences in comfort perceptions due to different fitting procedures. The earplugs were perceived to be more comfortable in the subject-fit condition than in the trained-fit condition.

Almost no significant difference in achieved attenuation or comfort was found between the 2 activity (jaw and work activity) movements, but the earmuff tended to slip more during highly kinematic work activity movement. In general, out of the 4 different HPD configurations used in the study, the foam plug was most resistant to the effects of either type of activity movement but did benefit more than the other devices from the training for proper fitting; it was also perceived as the most acceptable and stable HPD by the subjects.

In summary, the research illuminated the degrading influence of simulated field factors on HPD effectiveness and demonstrated that such factors could be modeled in a laboratory setting. In particular, the results demonstrated that trained user fitting techniques markedly improved attenuation levels for the earplug devices, but not for the earmuff. Activity movement and wearing time posed less of an influence than poor fitting on these selected HPDs, although there was a loss of attenuation over the period for all HPDs except the foam plug.

To ascertain the validity of estimating field HPD performance in a laboratory simulation protocol, both attenuation and comfort results from the field study (which will be discussed in the following sections) were directly comparable to those obtained in the laboratory study using the 3 HPDs common to both studies.

RESEARCH OBJECTIVES

In summary from the previous literature review, it is clear that the noise protection achieved by HPDs worn in the workplace is significantly less than that originally estimated in optimal laboratory conditions. This often large overestimation has been demonstrated through several empirical studies which predominantly evaluated insert-type devices using simple field real-ear attenuation at threshold (REAT) methods, such as the EAL method. On the other hand, field research on earmuffs and ear canal caps using REAT procedures is scant. Also, a recent laboratory simulation study (Park, 1989) revealed that certain field factors, such as HPD fitting procedure, significantly influence certain HPD's performance in the workplace. Following these laboratory-based findings (Casali and Park, 1990a; Park and Casali, 1991), the fundamental question remained as to how the laboratory attenuation and comfort results compare with those achieved under actual field conditions using 3 identical HPDs and user fitting protocols. In this regard, the field study described herein served as a validation test for the laboratory simulation results. In effect, since both the laboratory and field studies used 3 common HPDs, fitting conditions, and REAT testing procedures, the resultant data sets could be used to determine the accuracy and feasibility of applying a laboratory simulation for estimating actual field HPD performance.

This field study determined the actual field performance (i.e., attenuation and perceived comfort) of the 4 HPDs (user-molded foam and premolded flanged earplugs, a foam cushion earmuff, and a round-tipped canal cap) worn by industrial workers under different fitting conditions for a 3-week period. With the exception of the combination (muff/plug) protectors, those HPDs previously used in the laboratory simulation study (the foam earplug, the flanged earplug, and the foam cushion earmuff) were included in the sample for comparison purposes. The specific research aims were to:

1. Assess the actual amount of spectral noise reduction and wearer comfort achieved with several industrial HPDs in the field.

2. Investigate the effect of HPD fitting procedure (subject-fit versus trained-fit) on HPD performance in the workplace, and examine the effects of practice and experience with the device over 3 weeks of use.

3. Examine individual HPD susceptibility to influence by the HPD fitting effect.

4. Contrast the HPD attenuation and comfort performance results with those from the previous laboratory simulation study, and also compare the attenuation results with current manufacturer-provided data and with data from other field studies.

5. Devise, on the basis of the empirical data, a reliable field methodology that is convenient and simple to enable prediction of broadband noise protection, given only single one-third octave band test data.

Hypotheses

It was hypothesized that less attenuation and perhaps increased comfort would be achieved under the user-fit procedure than under the trained-fit, especially for insert-type devices. For instance, the amount of attenuation achieved by a user-molded foam earplug under the trained-fit condition would probably be greater than that obtained under the user-fit, due to the complexities of inserting the plug. The advantage, if any, might be less pronounced for a premolded polymer plug which requires less user manipulation. It was also expected that the HPD fitting effect (user-fit versus trained-fit) would be less for circumaural earmuff and semi-aural ear canal cap devices because they are generally considered to be easier to don than earplugs (Casali and Lam, 1986a). The outcomes of the current study were also expected to verify that field HPD performance is typically much less than manufacturers' laboratory data would indicate, which has not been demonstrated in EPA-required ANSI standard sound-field testing conditions, nor for earmuff and canal cap devices. For this purpose, both the spectral attenuation data obtained and the resulting NRR values were compared with corresponding manufacturers' data supplied with the devices. Finally, the results of this field research were used to assess the real-world validity of those from the laboratory simulation study conducted, with a similar experimental protocol, in the Auditory Systems Laboratory at Virginia Tech (Park, 1989). This has important implications for designing new, inter- and intra-laboratory repeatable HPD testing standards aimed at providing more realistic protection ratings. It was hypothesized that if the laboratory scenario posed a realistic simulation of workplace effects, then *attenuation and comfort obtained after the 2-hour activity period* (i.e., post-task laboratory data) might correspond most closely with those found in actual industrial work.

EXPERIMENTAL METHOD AND DESIGN

Subjects

Forty paid volunteer industrial workers, all males aged between 20 and 59 with mean of 37.9, participated in this study. They were recruited from industrial work sites around the Virginia Tech campus in Blacksburg, Virginia. Noise exposure levels of the work sites were measured using L_{OSHA}(5 dB exchange rate) with a Larson-Davis 800-B sound level meter, and the sites with 85 dBA (i.e., a projected dose of 50%, analogous to OSHA's [1988] trigger level of 85 dBA, TWA for instituting a hearing conservation program and supplying HPDs to workers) or higher noise levels were considered for selection of exposed employees as subjects. The measured noise levels were 90.8 dBA (a coal-fired electric power generating plant), 88.5 dBA (a printing press shop), 87.8/86.5 dBA (two metal cutting machine shops), 98.1 dBA (a carpentry shop), and 106.4 dBA (an airport: measured for 15 minutes during taxi activity only-- not an 8-hour TWA).

Subject screening

Each candidate for participation was welcomed and asked to read an overview description of the study (Appendix A). He was then screened for a portion of the qualifications using a pre-experimental questionnaire (Appendix B). The experimental procedures and subject's rights were next explained to the qualified participant (hereafter "subject"). The subjects, who currently used HPDs (not identical to the ones used in this study) in their workplaces, read and signed an informed consent document (Appendix C), indicating their willingness to participate.

After reading instructions for the hearing screening test (Appendix D), each subject entered the audiometric sound-treated chamber and underwent an audiometric test in accordance with ANSI S3.21-1978 (Methods for Manual Pure-Tone Audiometry). For each ear, the mean hearing threshold at each pure-tone frequency of 125, 250, 500, 1000, 2000, 4000, and 8000 Hz was determined by a Houghson-Westlake procedure (Morrill, 1986). Audiometric criteria used for subject selection included: (1) a hearing threshold level (HTL) of 40 dB or less at any test frequency in at least one ear, and (2) a left/right HTL difference of 20 dB or less at a minimum of 6 out of the 7 pure-tone test frequencies from 125 to 8000 Hz. The first criterion was to ensure that the hearing level plus HPD attenuation would be less than the maximum output of the current HPD test signal presentation system. The second criterion screened out persons who might not perform well in the binaural test for HPD attenuation in which the test signals were presented to both ears in a sound field. Subjects were accepted only if they met these 2 audiometric criteria. Subjects then practiced the psychophysical procedures for the HPD attenuation tests for familiarization purposes.

HPD Test Facility and Apparatus

The experimental facility used for the attenuation test has been electro-acoustically verified to be in accordance with ANSI S12.6-1984, the calibration data for which appear in Casali (1988). It includes a test booth (anechoic chamber), an IBM PS/2 Model 70 computer system with a VGA color display monitor (Model 8514) and two disk drives (a 3-1/2" and a 5-1/4" high density), and an integrated HPD test signal presentation and scoring/recording system (to be explained in the "HPD test system" section). The test facility is housed in the Auditory Systems Laboratory within the Department of Industrial and Systems Engineering at Virginia Tech.

Test booths

An Eckel Corporation anechoic chamber was used as the test booth for all attenuation testing. The outside and inside (between foam wedge tips) dimensions of the chamber are 3.7 x 4.3 x 3.5 m (12 x 14 x 11.5 ft) and 2.3 x 2.9 x 2.2 m (7.6 x 9.5 x 7.1 ft), respectively. A near-diffuse sound field is generated using four frequency response-matched loudspeakers located at corners of an imaginary tetrahedron surrounding the subject's head. The test facility meets ANSI S12.6-1984 acoustic specifications for HPD real-ear attenuation testing, as verified in Casali (1988). The Auditory Systems Laboratory has been accredited by the National Institute of Standards and Technology, National Voluntary Laboratory Accreditation Program (NVLAP) for HPD testing as per ANSI S3.19-1974 and ANSI S12.6-1984. Ambient noise levels for the anechoic chamber are presented in Table 2. Two-way communication (between the experimenter and the subject) is maintained via an intercom system. In addition, a closed-circuit television (CCTV) system was used for monitoring the subject during the test sessions.

Pure-tone audiometric screening tests were conducted in a semi-reverberant Industrial Acoustics Corporation (IAC) booth using the Beltone clinical audiometer (Model 114) and the Beltone subject's headphone (Model TDH-50P). The audiometric booth's octave band ambient noise levels are within those specified in ANSI S3.21-1978 (Table 2), "Methods for Manual Pure-Tone Audiometry."

Table 2. Ambient Noise Levels in the HPD Test Chamber and in the Audiometric Chamber.

Octave Band Center (Hz)	Permissible Ambient Level[1] for HPD Test Chamber (dB)	Actual Ambient Level in HPD Test Chamber (dB)	Permissible Ambient Level[2] for Audiometric Chamber (dB)	Actual Ambient Level in Audiometric Chamber (dB)
125	28.0	23.3	28.0	20.0
250	18.0	5.5	18.5	14.0
500	14.0	5.7	14.5	6.5
1000	14.0	7.5	14.0	4.5
2000	8.0	5.6	8.5	2.7
4000	9.0	7.3	9.0	5.1
8000	20.0	9.3	20.5	8.1

[1] As per Table I, ANSI S12.6-1984.

[2] As specified in ANSI S3.21-1978 (p. 3) and actually presented in Table C1, ANSI S3.1-1977.

HPD test system

A fully integrated, IBM PS/2 (Model 70)-controlled HPD test system (Norwegian Electronics Type 828), which includes test signal generation, amplification and control apparatus, and 4 loudspeakers (TEP S-2), was used to perform all psychophysical HPD attenuation tests. The system was used in an automatic Békésy audiometry (Békésy, 1960) mode. In this mode, the subject controls the signal attenuation by pressing a button as long as the signal is heard, which then causes the signal level to decrease at a predetermined rate. The subject then releases the button when the signal is not heard, which in turn causes the signal level to increase at the same predetermined rate. This Békésy method of "tracking" threshold using an attenuator rate of 5 dB/sec in 1 dB steps was applied for the current study. The test system provides threshold tests for one-third octave band noise centered at 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz and pulsed on and off at a rate of 2 Hz. All results were plotted in dB hearing threshold level as a function of test frequency using an Epson LX-800 dot-matrix printer interfaced with the IBM computer.

HPD test system calibration

Signals in the audiometric facility and the HPD test facility were calibrated with a Larson-Davis Model 800-B precision sound level meter and one-third octave analyzer, with ACO Model 7013 half-inch microphone and Larson-Davis Model 825-10 preamplifier. This device meets ANSI S1.4-1971 (Type 1) for precision sound measurement equipment. The sound levels at the subject's ear height position were set using the minimum audible field (MAF) curve presented in Table 3, corrected for room response, with baseline calibration performed at the 40 dB hearing threshold level. The MAF values in Table 3 were modified from those of ISO (1961) and Berger

Table 3. Minimum Audible Field (MAF) Determination.

ANSI Test Frequency[1] (Hz)	Free Field MAF[2] (dB) [1]	Free to Diffuse Correction[3] (dB) [2]	Diffuse Field MAF[4] (dB) [1] + [2]
125	27.9	0.0	27.9
250	15.8	0.0	15.8
500	7.4	-1.0	6.4
1000	3.0	-2.5	0.5
2000	1.0	2.0	3.0
3150	-2.9	2.0	-0.9
4000	-3.9	1.5	-2.4
6300	4.6	-2.0	2.6
8000	15.3	-5.0	10.3

[1] 1/3-octave band center frequency.

[2] Values for 125 - 1000 Hz are from Table 4 of Berger (1981a), and values for 2000 - 8000 Hz are from ISO (1961).

[3] Modified (sign-changed) from Table 3 of Berger (1981a).

[4] Used for test system calibration.

(1981a). Signal level equalization between the 4 speakers was calibrated on a daily basis.

A Brüel and Kjær standard source calibrator (Type 4230) was used for Larson-Davis Model 800-B analyzer/microphone calibration, and a Larson-Davis artificial ear (Model AE100), with headphone coupler and a 1-inch ACO Model 7023 microphone, was used for audiometer calibration.

Experimental Design

The experimental design used for data collection and analysis was a 3-way, complete factorial, mixed-factors design, i.e., a 4 x 2 x 3 (HPD type x fitting procedure x time of use) design where all variables were within-subjects except a between-subjects factor of HPD type. Ten subjects were randomly assigned to each HPD and each experimental cell (Figure 4), and each subject subsequently attended 8 laboratory sessions (2 HPD fitting sessions and 6 data collection sessions). All independent variables were treated as fixed-effects variables, and subjects were treated as random-effects.

Independent variables

The 3 factors for the experimental design were HPD type, HPD fitting procedure, and time of use.

HPD type: For this study, HPDs from the following major manufacturers were considered: Bilsom International, E-A-R, Elvex, Flents, Howard Leight, Moldex, MSA, Norton, and Willson Safety Products. Product literature and HPD samples from these

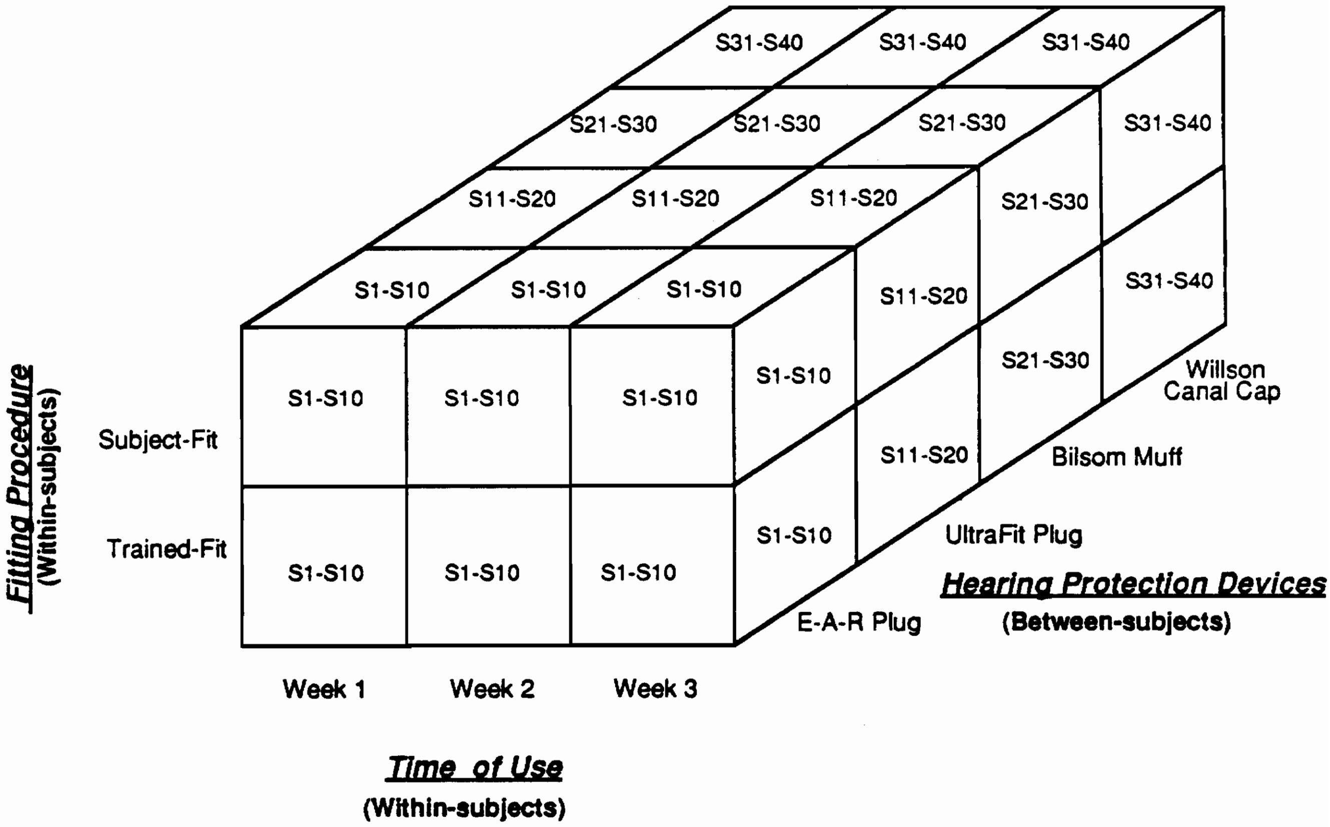

Figure 4. Experimental design matrix.

vendors were received and reviewed. HPDs were selected based on diversity in style, popularity of use in the field, and range of protection levels.

HPD type, a between-subjects variable, included the E-A-R foam earplug (user-molded), E-A-R "UltraFit" triple-flanged polymer earplug (premolded), Bilsom UF-1 universal foam cushion earmuff, and Willson "Sound-Ban" Model 20 ear canal cap. As mentioned earlier, 3 HPDs from the previous laboratory study (E-A-R foam plug, UltraFit triple-flanged plug, and Bilsom UF-1 muff) were again used for comparison purposes. The canal cap was not used in the laboratory study because in pilot testing most subjects reported discomfort in wearing it (and several other varieties of canal caps) continuously for the 2-hour wearing period. Canal caps are often recommended for intermittent use in instances where wearers need to quickly don and doff their HPDs. The 4 HPDs used in the current study are illustrated in the photograph in Figure 5. A brief description of each device and its most recent manufacturer's labeled NRR value *just prior to commencement of the study* are as follows:

- E-A-R foam plug: A cylindrical, formable earplug made of slow-recovery foam that is to be rolled, compressed into a small diameter cylinder, quickly inserted into the ear canal, and allowed to expand to provide a seal. The labeled NRR is 29 dB, as tested per ANSI S3.19-1974.

- E-A-R UltraFit triple-flanged plug: A soft, premolded polymer earplug with 3 hemispherical flanges of decreasing radii toward the tip of the stem, which provides for fingertip grasp during insertion. The labeled NRR is 27, as tested per ANSI S12.6-1984.

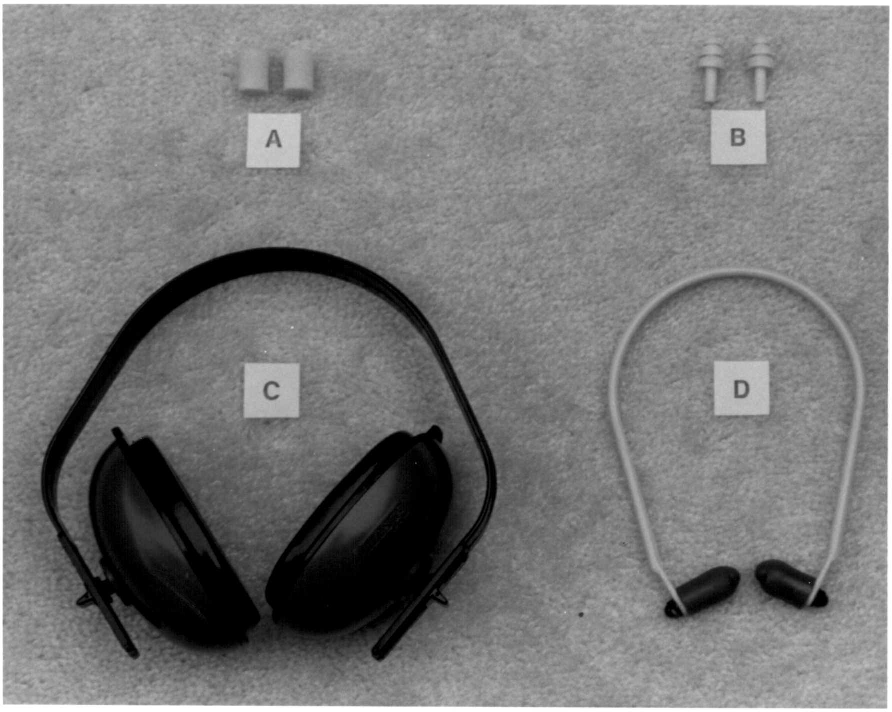

Figure 5. Hearing protection devices used in the study: (A = E-A-R slow-recovery foam earplug; B = UltraFit polymer triple-flanged earplug; C = Bilsom UF-1 foam cushion earmuff; D = Willson Sound-Ban 20 ear canal cap).

- Bilsom UF-1 universal earmuff: A lightweight (163 g), popular foam cushion earmuff with adjustable gimball-mounted earcups. Headband force measured at an earcup separation of 14.35 cm and headband height of 13.08 cm (re ANSI S12.6-1984) was 11.8 N. The labeled NRR is 25 dB, as tested over the head in accordance with ANSI S3.19-1974.

- Willson Sound-Ban canal cap: A semi-aural device with round-tipped rubber pods that occlude the rim of the ear canal and are connected by a flexible plastic headband. The labeled NRR is 22 dB, as tested per ANSI S3.19-1974 for under the chin fitting, where workers in the study wore the headband.

Subjects were initially supplied with an HPD, which they had not used before, for the first 3-week period of use, so the influence of the initial fitting procedure (on later attenuation achieved) could be determined.

HPD fitting procedure: HPD fitting procedure was a within-subjects variable and consisted of two distinct levels: "subject-fit" and "trained-fit." In the subject-fit procedure, the subject worker was handed the HPD in its standard industrial package and simply told to wear it while on the job for the first 3-week period. Only the manufacturer's package instructions (Appendix E) were available for the subject to use in donning the HPD. No experimenter intervention/assistance (verbal or physical) was given, and the subject was not allowed to ask any questions regarding the fitting procedures. The subject condition, which mimicked many industrial practices where workers fit their HPDs with no supervision, always preceded the trained-fit condition so that the subject-fit procedure was not pre-biased by the experimenter training.

On the other hand, in the trained-fit condition (which was presented after 3 weeks of use under subject-fit), the subject read the manufacturer's instructions and learned the proper fitting procedure from the experimenter's demonstration, on himself, of the step-by-step procedure for placing the HPD to obtain an optimal noise seal. However, the experimenter did not augment or embellish the manufacturer's instructions, nor did he physically place the HPD on the subject's head. The subject practiced donning the HPD while receiving verbal feedback and answers to questions from the experimenter.

Time of use: Time period of HPD use was also a within-subjects variable with 3 levels, week 1, 2, and 3, under each fitting condition. The subject, while wearing the HPD under each fitting condition, returned to the laboratory for three data collection sessions, with one session during each of the first, second, and third weeks after the fitting session. This variable allowed examination of the effects of practice/experience with the device over the period.

Dependent measures

Spectral attenuation (in dB) and comfort ratings constituted the dependent measures for all experimental conditions. Nine attenuation data values from each of the 9 test frequencies were collected in each experimental session using the REAT method (as discussed previously) in accordance with ANSI S12.6-1984. A single-number comfort index calculated from the subject's responses to a series of bipolar comfort rating scales, also obtained during each session, served as the other dependent measure.

Although not used as a dependent measure, each subject's daily HPD wearing time was estimated by a self-report questionnaire (Appendix F) distributed daily to the workers at the work sites. Based on a 8-hour daily work-shift, an estimated average daily wearing time for each HPD is reported in Appendix G.

Experimental Procedure

Each subject attended 4 sessions for each fitting procedure condition: the HPD fitting session, followed by 3 data collection sessions, with at least 1 week between sessions.

HPD fitting session

The first HPD fitting session, for the subject-fit procedure, was held immediately following audiometric screening and prior to the first 3-week period of HPD use. The subject read the instructions for the subject-fit procedure (Appendix H) and was handed the HPD in its industrial package. Then, he was told to return to his work site with the assigned HPD and to wear it (i.e., using only the manufacturer's instructions: Appendix E) for the 3-week period.

The second HPD fitting session, for the trained-fit condition, was presented prior to the second 3-week HPD use period, i.e., after the third data collection visit with the subject-fit condition. The subject read the instructions for the trained-fit procedure (Appendix I) and was trained by the experimenter as explained previously. After this training session, the subject was instructed to return to the workplace and to wear the HPD exactly as learned in the training session for the remainder of the experimental period (i.e., for the second 3-week period).

After the initial fitting session with the subject for either fitting procedure, no further instructions were given for the ensuing 3-week usage period in the field.

Experimental data collection sessions

Each of the 3 data collection sessions for each fitting condition lasted approximately 1 hour and involved collecting a set of attenuation and comfort rating data. During the 3-week use period under each assigned fitting condition, the subject was pulled (unannounced) from the workplace on 3 separate occasions (once per week), and 3 sets of attenuation and comfort data were obtained for the HPD, as it was found worn by the subject on the job. Subjects did not know when they were to be tested, as this was determined randomly with the only time constraint being a minimum of 1 week between tests, but they were aware that they were going to be tested 3 times during each 3-week period. Also, subjects were pulled at least 1 hour following the start of a work-shift.

At the predetermined but unannounced time in the work site, the subject was greeted by the experimenter. Using an 8-1/2″ x 11″ hand-held sign (Appendix J) to preclude the necessity of talking, the subject was instructed that it was time to be escorted to the Auditory System Laboratory at Virginia Tech for testing and not to adjust his HPD. In the case that the subject was not wearing the HPD at the time when the experimenter arrived at the work site to pick him up, the scheduled testing session was cancelled. Consequently, the subject was pulled at a later unannounced time. This situation occurred only once for the current study. For all subjects, the trip to the laboratory was short (i.e., a maximum of 5 minutes) and was made in an experimenter's car across campus. The subject was constantly accompanied by the experimenter and was required to hold (to occupy his hands and avoid touching the HPD) a set of detailed attenuation test instructions (Appendix K) until arrival at the test chamber, where the instructions were read. Once the subject entered the test chamber, a closed-circuit television (CCTV) and intercom system was used to monitor and converse with the subject to help ensure that no HPD readjustment occurred. These procedures helped enable the collection of the most realistic workplace attenuation (under sound-field REAT protocol) and comfort data, representative of actual performance levels achieved by the worker using his HPDs on the job.

Each experimental session primarily consisted of 4 hearing threshold tests (2 occluded-ear and 2 unoccluded-ear) and comfort ratings. As a re-familiarization procedure at the beginning of each session, the subject practiced automatic threshold tracking for 1 trial each at 9 test frequencies in the test chamber. Then, he underwent 2 occluded-ear threshold tests and performed comfort ratings using the scales shown in Appendix M, while still wearing the HPD as found at the work site. Next, the subject doffed the HPD and was given a 5-minute break. (During only the third experimental session under each fitting condition, the subject also performed overall HPD convenience ratings using the scales shown in Appendix N.) Finally, he underwent 2 unoccluded-ear threshold tests. Each subject was debriefed and paid $50 at the end of the last experimental session with the trained-fit condition. For recapitulation, the sequence of experimental protocol steps is presented in Table 4.

At the conclusion of each experimental session, the physical condition of the subject's HPD was inspected visually by the experimenter. If needed, the earmuff and the ear canal cap were replaced at this time. Also, they were replaced at any time when the subject requested in the field. Boxes containing each earplug under study were placed at each work site so that subjects could replace their earplugs as needed.

HPD attenuation test protocol

In all experimental conditions, attenuation data were obtained using the real-ear attenuation at threshold (REAT) method in accordance with the ANSI

Table 4. Protocol for Experimental Sessions.

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1. Subject employee is approached (unannounced) by experimenter at job site and instructed, via a hand-held sign (Appendix J), that it is time for a hearing test and not to touch the HPD.
2. Subject is handed instruction sheet for HPD attenuation test (Appendix K).
3. Subject is transported, by car, to the testing laboratory. (Maximum of five minutes elapsed time.)
4. Subject reads instructions for HPD attenuation test (Appendix K).
5. Subject enters the HPD-test chamber, and a practice trial for the REAT test is presented.
6. Subject undergoes two *occluded-ear* threshold tests, while wearing the HPD as found at the worksite.
7. Subject exits the chamber and reads Instructions for HPD Comfort Rating Scales (Appendix L).
8. Subject performs the HPD Comfort Ratings (Appendix M) while still wearing the HPD.
9. Subject doffs the HPD and is given a five-minute break.
10. For the third experimental session only, subject performs overall HPD Convenience Ratings (Appendix N).
11. Subject re-enters the chamber and undergoes two *unoccluded-ear* threshold tests.
12. At close of the third experimental session with the trained-fit condition, subject is debriefed and paid.

S12.6-1984 standard, as previously indicated. Using open-air, loudspeaker-presented signals, both unoccluded (without an HPD) and occluded (with an HPD) thresholds were obtained for each of 9 one-third octave bands. The Békésy automatic tracking method (explained previously) was used to establish dB threshold at each one-third octave band (test frequency, hereafter). The mean audiogram value over a minimum of 8 trace excursions (between 4 ″peak″ reversals and 4 ″valley″ reversals), scored by the computer, was taken as the subject's hearing threshold to the nearest tenth of a dB at a given frequency. The sequence of frequency presentations was from 125 to 8000 Hz, with a return to 125 Hz for a reliability check at the end of each trial.

The difference (in dB) between the occluded and unoccluded threshold was considered as the attenuation (i.e., noise reduction) of the HPD at each frequency. At each test band frequency, attenuation for each HPD in each fitting condition in this field study was obtained by the data reduction procedure discussed in the ″Spectral Attenuation Data Analysis″ section later. For each of the 9 test frequencies, 3 sets of spectral attenuation data for an HPD were obtained under each fitting condition, 1 for each of the 3 experimental sessions. The spectrum of resultant attenuation data for the selected HPD was used for computation of an NRR value for that HPD, which requires 3 attenuation measurements at each frequency per subject (or 30 attenuation scores at each frequency for 10 subjects, as per ANSI S12.6-1984). This calculated NRR value for each HPD was then compared with the corresponding manufacturer's NRR value (as discussed later in the ″RESULTS: ATTENUATION DATA″ section).

Comfort and convenience ratings protocol

The comfort ratings were obtained using a proven set of bipolar adjective rating scales used in the predecessor laboratory study (Park, 1989). Similar rating scales, developed and investigated by Casali et al. (1987), have since been validated and iteratively improved across several studies. As indicated in Table 4, the subject provided comfort ratings just after the second occluded threshold trial. The subject responded to a set of bipolar comfort rating scales, presented in Appendix M. A single-number comfort index was then calculated (as explained later in the "RESULTS: COMFORT DATA" section) for comfort data analysis.

After the subject finished all occluded-ear threshold tests in the third experimental session and then doffed the HPD (Table 4), he completed a set of bipolar convenience rating scales (Appendix N). This convenience rating reflected the subject's overall experience with and impression of the HPD, after having used it for the 3-week period on the job. The convenience ratings were used in a descriptive analysis as is later discussed in the "RESULTS: COMFORT DATA" section.

RESULTS: ATTENUATION DATA

The attenuation data analyses were performed primarily on spectral attenuation data obtained at 9 one-third octave test bands. In addition, frequency-collapsed Noise Reduction Rating (NRR) scores were computed to enable simple HPD comparisons on a single-number rating, rather than frequency-specific, basis. Parametric statistical procedures were employed for data analyses on the IBM 3091 mainframe computer using the Statistical Analysis System (SAS, 1990) computer package.

Spectral Attenuation Data Analysis

The objectives of the spectral attenuation data analysis were to (1) determine the effect of HPD fitting procedure (subject-fit versus trained-fit) and period of HPD use on frequency-specific field HPD protection levels and (2) investigate individual HPD susceptibility to influence by each of these factors.

Data reduction

As explained previously in the "Experimental Procedure" section, for each experimental session, 2 occluded and 2 unoccluded thresholds for each subject were obtained at each test band frequency. Paired *t*-tests (with a reference statistic of $t_{0.05}(239) = 1.97$) were first performed to determine if the 2 occluded thresholds at each test frequency were statistically different from each other; likewise the 2 unoccluded thresholds were *t*-tested. Since there existed no significant ($p < 0.05$)

differences between the 2 occluded thresholds and also between the 2 unoccluded thresholds at all test frequencies, the 2 occluded thresholds (likewise the 2 unoccluded thresholds) were averaged, resulting in a single pair of occluded and unoccluded thresholds. Then, the difference (in dB) between these occluded and unoccluded thresholds was taken as the attenuation of the HPD at each test frequency, and this was used as the dependent measure at that frequency. In this manner, a set of 9 spectral attenuation values was obtained for the subject in each session. The resultant data set for each experimental cell was complete, as all 40 subjects attended all 6 data collection sessions. Attenuation means and standard deviations for each experimental condition are presented in Table 5.

Overall ANOVA

Since attenuation scores were obtained independently for each of the 9 test bands, a series of 9 mixed-factors ANOVAs was performed, one on each test frequency dependent measure; ANOVA summary tables are presented in Tables 6 through 14. Significant ($p < 0.05$) interaction effects included fitting procedure-by-time of use-by-HPD (F x T x H) and fitting procedure-by-time of use (F x T) both at 2000 Hz and below, fitting procedure-by-HPD (F x H) at all frequencies except 2000 - 4000 Hz, and time of use-by-HPD (T x H) at the lower frequency spectrum of 125 - 500 Hz. Statistically significant ($p < 0.05$) main effects were very consistent across the test spectrum and were found for fitting procedure (F) at all 9 frequencies and for HPD (H) at all frequencies except 8000 Hz. All significant interactions and main effects were subjected to additional post-hoc tests for further investigation of the loci of significance. These post-hoc analyses were performed in a "funneling" fashion to isolate specific effects of interest and to conserve statistical

Table 5. Field Attenuation Means (Standard Deviations) in dB for Each Experimental Condition

HPD	Fitting Condition	Time of Use (Week)	1/3-Octave Test Band Center Frequency (Hz) 125	250	500	1000	2000	3150	4000	6300	8000
E-A-R Foam Earplug	Subject-Fit	W_1	17.0 (9.6)	17.8 (11.5)	20.0 (12.3)	19.4 (11.7)	29.5 (10.0)	34.3 (12.5)	33.3 (11.2)	31.7 (11.3)	29.8 (9.7)
		W_2	10.6 (8.9)	10.2 (11.8)	12.8 (12.7)	14.0 (13.8)	23.2 (15.2)	27.0 (14.6)	26.4 (12.3)	25.5 (14.0)	24.3 (9.9)
		W_3	13.5 (11.7)	15.1 (12.7)	16.9 (15.1)	16.9 (14.6)	27.0 (14.2)	32.3 (12.1)	30.3 (11.1)	29.3 (15.3)	28.7 (12.4)
	Trained-Fit	W_1	20.5 (9.7)	23.9 (9.9)	27.2 (11.7)	27.6 (10.6)	31.1 (6.9)	37.4 (4.8)	35.8 (5.8)	37.8 (8.3)	35.3 (8.1)
		W_2	26.3 (9.2)	28.4 (9.1)	33.0 (9.2)	32.5 (6.2)	34.7 (4.0)	38.7 (3.6)	38.2 (3.5)	40.8 (9.4)	37.2 (6.0)
		W_3	28.2 (5.6)	29.6 (5.8)	33.2 (7.2)	32.3 (6.0)	34.9 (3.8)	38.5 (3.1)	36.3 (3.6)	38.5 (9.2)	36.3 (6.1)
Bilsom UF-1 Earmuff	Subject-Fit	W_1	9.9 (4.7)	13.0 (3.7)	19.7 (5.3)	25.7 (7.1)	26.4 (6.5)	34.5 (3.8)	35.9 (6.0)	37.3 (7.3)	34.7 (8.2)
		W_2	7.6 (4.4)	12.4 (5.1)	19.3 (5.5)	26.3 (6.9)	25.2 (6.2)	34.1 (4.4)	34.8 (7.9)	36.2 (8.5)	35.9 (7.1)
		W_3	7.6 (3.4)	11.4 (4.8)	19.0 (5.3)	27.5 (6.4)	26.9 (4.1)	34.1 (2.8)	37.4 (6.3)	37.0 (5.7)	35.1 (6.3)
	Trained-Fit	W_1	8.6 (1.9)	12.8 (2.6)	20.3 (2.5)	26.6 (4.1)	28.0 (4.3)	37.0 (3.3)	38.7 (5.4)	37.2 (5.6)	35.7 (5.3)
		W_2	9.8 (2.9)	14.5 (2.7)	22.0 (3.2)	28.0 (3.7)	28.3 (3.3)	35.9 (2.8)	38.2 (5.5)	38.4 (5.6)	36.4 (6.1)
		W_3	9.7 (2.8)	14.4 (3.0)	20.8 (2.6)	27.3 (3.7)	29.4 (4.0)	36.5 (2.7)	38.2 (5.2)	37.2 (5.6)	36.0 (5.9)
Ultra Fit Earplug	Subject-Fit	W_1	14.9 (9.8)	15.3 (10.0)	15.8 (11.6)	17.1 (11.7)	22.0 (10.1)	26.1 (10.0)	23.2 (11.3)	19.4 (11.6)	21.5 (9.1)
		W_2	9.8 (7.1)	11.9 (8.9)	12.4 (8.9)	14.5 (9.9)	19.0 (9.9)	22.6 (6.7)	20.0 (7.4)	17.2 (11.0)	20.6 (13.0)
		W_3	4.5 (5.7)	5.7 (6.1)	7.4 (6.9)	9.7 (8.5)	16.9 (8.2)	22.0 (5.9)	19.0 (7.0)	16.9 (9.1)	17.8 (10.8)
	Trained-Fit	W_1	17.7 (4.6)	18.0 (5.6)	19.0 (6.1)	20.0 (5.2)	25.1 (1.2)	28.2 (5.0)	28.0 (7.3)	30.1 (7.2)	33.9 (7.5)
		W_2	19.1 (3.7)	19.8 (3.3)	20.9 (2.5)	21.1 (3.3)	25.5 (3.1)	28.4 (3.0)	28.1 (5.8)	29.9 (2.9)	33.7 (5.9)
		W_3	19.3 (5.5)	20.1 (6.0)	19.0 (6.1)	22.2 (5.0)	27.3 (5.6)	28.9 (4.9)	28.1 (5.4)	30.2 (6.7)	32.1 (7.6)
Willson Sound-Ban 20 Canal Cap	Subject-Fit	W_1	12.9 (7.3)	12.7 (8.4)	12.0 (5.4)	12.3 (7.6)	26.1 (7.0)	31.1 (7.6)	30.7 (8.7)	29.1 (11.9)	28.1 (13.4)
		W_2	14.1 (8.9)	13.5 (8.8)	12.0 (7.3)	10.8 (8.3)	26.9 (8.1)	32.6 (7.0)	32.0 (10.0)	32.5 (13.8)	29.5 (15.2)
		W_3	13.0 (9.0)	12.2 (8.9)	12.4 (8.6)	12.2 (10.2)	27.6 (6.3)	32.7 (5.0)	31.8 (7.4)	31.7 (12.1)	30.9 (12.7)
	Trained-Fit	W_1	16.4 (5.3)	15.9 (6.1)	13.8 (5.0)	15.0 (5.4)	29.7 (5.7)	34.2 (5.3)	32.5 (8.6)	33.3 (11.8)	33.5 (11.8)
		W_2	17.1 (7.4)	16.0 (5.6)	15.8 (6.1)	15.0 (7.1)	28.4 (6.7)	34.8 (5.2)	32.7 (8.0)	33.4 (10.7)	33.6 (11.3)
		W_3	16.2 (6.9)	16.9 (5.8)	16.5 (6.2)	16.0 (6.5)	30.3 (3.9)	34.3 (5.5)	32.7 (8.7)	34.0 (9.7)	32.9 (10.3)

Table 6. ANOVA Summary Table for Field Attenuation in dB at 125 Hz

Source	*df*	*SS*	*F*	*p*
Between-Subjects				
HPD Type (H)	3	3328.15	5.95	0.0021
Subjects (S/H)	36	6717.04		
Within-Subjects				
Fitting Procedure (F)	1	2268.74	44.17	0.0001
F x H	3	1043.06	6.77	0.0010
F x S/H	36	1849.15		
Time of Use (T)	2	22.26	0.85	0.4316
T x H	6	253.55	3.23	0.0073
T x S/H	72	942.50		
F x T	2	490.30	16.23	0.0001
F x T x H	6	363.33	4.01	0.0016
F x T x S/H	72	1087.73		
Total	239	18365.81		

Table 7. ANOVA Summary Table for Field Attenuation in dB at 250 Hz

Source	*df*	*SS*	*F*	*p*
Between-Subjects				
HPD Type (H)	3	2087.00	3.02	0.0420
Subjects (S/H)	36	8280.10		
Within-Subjects				
Fitting Procedure (F)	1	2625.82	53.35	0.0001
F x H	3	1161.32	7.87	0.0004
F x S/H	36	1771.75		
Time of Use (T)	2	9.62	0.33	0.7176
T x H	6	242.02	2.80	0.0168
T x S/H	72	1038.82		
F x T	2	418.41	13.33	0.0001
F x T x H	6	343.09	3.64	0.0033
F x T x S/H	72	1130.05		
Total	239	19107.99		

Table 8. ANOVA Summary Table for Field Attenuation in dB at 500 Hz

Source	*df*	*SS*	*F*	*p*
Between-Subjects				
HPD Type (H)	3	3679.39	4.74	0.0069
Subjects (S/H)	36	9312.97		
Within-Subjects				
Fitting Procedure (F)	1	2798.59	53.19	0.0001
F x H	3	1511.33	9.57	0.0001
F x S/H	36	1894.12		
Time of Use (T)	2	6.02	0.17	0.8450
T x H	6	271.22	2.54	0.0277
T x S/H	72	1283.29		
F x T	2	386.45	11.56	0.0001
F x T x H	6	251.34	2.51	0.0294
F x T x S/H	72	1203.51		
Total	239	22598.22		

Table 9. ANOVA Summary Table for Field Attenuation in dB at 1000 Hz

Source	*df*	*SS*	*F*	*p*
Between-Subjects				
HPD Type (H)	3	6552.33	7.66	0.0004
Subjects (S/H)	36	10262.90		
Within-Subjects				
Fitting Procedure (F)	1	2472.98	41.93	0.0001
F x H	3	1481.31	8.37	0.0002
F x S/H	36	2123.43		
Time of Use (T)	2	2.86	0.09	0.9162
T x H	6	123.50	1.26	0.2866
T x S/H	72	1175.98		
F x T	2	233.01	7.52	0.0011
F x T x H	6	305.41	3.29	0.0065
F x T x S/H	72	1115.14		
Total	239	25848.85		

Table 10. ANOVA Summary Table for Field Attenuation in dB at 2000 Hz

Source	*df*	*SS*	*F*	*p*
Between-Subjects				
HPD Type (H)	3	1788.01	2.99	0.0436
Subjects (S/H)	36	7174.91		
Within-Subjects				
Fitting Procedure (F)	1	1308.30	19.32	0.0001
F x H	3	281.95	1.39	0.2622
F x S/H	36	2438.37		
Time of Use (T)	2	56.13	1.82	0.1687
T x H	6	48.45	0.52	0.7876
T x S/H	72	1107.66		
F x T	2	141.24	4.74	0.0117
F x T x H	6	255.10	2.85	0.0151
F x T x S/H	72	1073.81		
Total	239	15673.93		

Table 11. ANOVA Summary Table for Field Attenuation in dB at 3150 Hz

Source	*df*	*SS*	*F*	*p*
Between-Subjects				
HPD Type (H)	3	3332.71	7.29	0.0006
Subjects (S/H)	36	5484.56		
Within-Subjects				
Fitting Procedure (F)	1	1007.78	17.72	0.0002
F x H	3	243.34	1.43	0.2511
F x S/H	36	2047.64		
Time of Use (T)	2	47.62	1.63	0.2031
T x H	6	111.96	1.28	0.2785
T x S/H	72	1051.66		
F x T	2	73.92	2.38	0.0997
F x T x H	6	184.87	1.99	0.0789
F x T x S/H	72	1117.41		
Total	239	14703.46		

Table 12. ANOVA Summary Table for Field Attenuation in dB at 4000 Hz

Source	*df*	*SS*	*F*	*p*
Between-Subjects				
HPD Type (H)	3	5211.24	7.62	0.0005
Subjects (S/H)	36	8207.38		
Within-Subjects				
Fitting Procedure (F)	1	1151.28	18.26	0.0001
F x H	3	435.03	2.30	0.0938
F x S/H	36	2270.05		
Time of Use (T)	2	36.76	0.91	0.4080
T x H	6	85.71	0.71	0.6461
T x S/H	72	1457.80		
F x T	2	90.12	2.53	0.0867
F x T x H	6	202.96	1.90	0.0926
F x T x S/H	72	1282.40		
Total	239	20430.73		

Table 13. ANOVA Summary Table for Field Attenuation in dB at 6300 Hz

Source	*df*	*SS*	*F*	*p*
Between-Subjects				
HPD Type (H)	3	5751.60	4.89	0.0059
Subjects (S/H)	36	14115.98		
Within-Subjects				
Fitting Procedure (F)	1	2478.77	24.72	0.0001
F x H	3	1433.80	4.77	0.0067
F x S/H	36	3609.51		
Time of Use (T)	2	2.31	0.06	0.9456
T x H	6	80.72	0.65	0.6878
T x S/H	72	1484.05		
F x T	2	67.30	1.47	0.2368
F x T x H	6	217.54	1.58	0.1644
F x T x S/H	72	1648.45		
Total	239	30890.03		

Table 14. ANOVA Summary Table for Field Attenuation in dB at 8000 Hz

Source	*df*	*SS*	*F*	*p*
Between-Subjects				
HPD Type (H)	3	2479.71	2.24	0.1000
Subjects (S/H)	36	13267.73		
Within-Subjects				
Fitting Procedure (F)	1	2647.70	28.06	0.0001
F x H	3	1353.64	4.78	0.0066
F x S/H	36	3397.27		
Time of Use (T)	2	4.81	0.11	0.8917
T x H	6	140.09	1.11	0.3630
T x S/H	72	1509.57		
F x T	2	31.16	0.70	0.5015
F x T x H	6	150.66	1.12	0.3576
F x T x S/H	72	1609.69		
Total	239	26592.02		

power. Simple effect *F*-tests or simple interaction effect *F*-tests (Keppel, 1982) were followed by pairwise means comparisons tests, including Bonferroni-*t* and Newman-Keuls as appropriate. All post-hoc tests were performed at the $p < 0.05$ level unless noted otherwise.

Fitting procedure-by-time of use-by-HPD interaction: This 3-way interaction (F x T x H) was further addressed using simple interaction effect *F*-tests (Table 15) to determine if a significant F x T interaction effect on each HPD existed. According to the results, the F x T interaction changed significantly ($p < 0.01$) with both insert-type HPDs (E-A-R foam and UltraFit earplugs), while no significant changes were found with either the earmuff or ear canal cap devices.

For each of the 2 earplugs, further simple effect *F*-tests (Table 16) were applied to investigate attenuation changes over time under each fitting procedure, followed by Bonferroni *t*-tests (Table 17). Based on the Bonferroni results, Figure 6 illustrates the time effect on each earplug's attenuation under each fitting condition at 2000 Hz and below. The UltraFit plug showed a gradual decrease in attenuation over the 3-week period under the subject-fit condition, but no significant ($p < 0.05$) change under the trained-fit condition. The foam plug, on the other hand, revealed a different trend. Under subject-fit, no significant attenuation difference occurred between the first and third week (evidenced by an attenuation loss after 2 weeks of use, followed by an increase in the third week back to initial attenuation levels). However, improved attenuation due to training was apparent after 2 weeks under trained-fit.

Fitting procedure-by-time of use interaction: The interaction effect of fitting procedure with time (F x T) was also significant ($p < 0.05$) at 2000 Hz and below. (Note that the results of the F x T interaction are restricted by the 3-way interaction

Table 15. Simple Interaction Effect *F*-Test[1] Summary Table for the Fitting Procedure-by-Time of Use-by-HPD (F x T x H) Interaction Post-hoc Analysis (Attenuation in dB)

Center Freq. (Hz)		125	250	500	1000	2000
HPD[2]	Statistics					
U	MS_{FxT}	180.08	170.87	92.82	120.04	65.32
	$MS_{FxTxS(H)}$	15.11	15.70	16.72	15.49	14.91
	F[3]	11.92	10.88	5.55	7.75	4.38
	p	<0.01	<0.01	<0.01	<0.01	<0.05
E	MS_{FxT}	226.09	189.22	212.79	141.61	125.08
	$MS_{FxTxS(H)}$	15.11	15.70	16.72	15.49	14.91
	F[3]	14.96	12.05	12.73	9.14	8.39
	p	<0.01	<0.01	<0.01	<0.01	<0.01
B	MS_{FxT}	20.33	14.02	4.80	4.54	2.46
	$MS_{FxTxS(H)}$	15.11	15.70	16.72	15.49	14.91
	F[3]	1.35	0.89	0.29	0.29	0.16
	p	>0.05	>0.05	>0.05	>0.05	>0.05
W	MS_{FxT}	0.33	6.64	8.50	3.03	5.32
	$MS_{FxTxS(H)}$	15.11	15.70	16.72	15.49	14.91
	F[3]	0.02	0.42	0.51	0.20	0.36
	p	>0.05	>0.05	>0.05	>0.05	>0.05

[1] To determine differences due to fitting procedure-by-time of use (F x T) interaction for each HPD.

[2] U = UltraFit flanged plug; E = E-A-R foam plug; B = Bilsom muff; W = Willson canal cap

[3] $F = \frac{MS_{FxT}(df = 2)}{MS_{FxTxS(H)}(df = 72)}$; $F_{(.05,\,2,\,72)} = 3.13$; $F_{(.01,\,2,\,72)} = 4.94$

Table 16. Simple Effect *F*-Test[1] Summary Table for the Fitting Procedure-by-Time of Use-by-HPD (F x T x H) Interaction Post-hoc Analysis (Attenuation in dB)

Center Freq. (Hz)			125	250	500	1000	2000
HPD[2]	Fit	Statistics					
U	Subject-Fit	MS_T	269.64	233.28	179.84	142.94	63.32
		$MS_{FxTxS(H)}$	15.11	15.70	16.72	15.49	14.91
		F[3]	17.85	15.72	10.76	9.23	4.25
		p	<0.01	<0.01	<0.01	<0.01	<0.05
U	Trained-Fit	MS_T	7.46	13.52	11.49	12.89	14.21
		$MS_{FxTxS(H)}$	15.11	15.70	16.72	15.49	14.91
		F[3]	0.49	0.86	0.69	0.83	0.95
		p	>0.05	>0.05	>0.05	>0.05	>0.05
E	Subject-Fit	MS_T	99.94	146.68	121.73	75.37	98.74
		$MS_{FxTxS(H)}$	15.11	15.70	16.72	15.49	14.91
		F[3]	6.61	9.34	7.28	4.87	6.62
		p	<0.01	<0.01	<0.01	<0.01	<0.01
E	Trained-Fit	MS_T	158.80	89.60	115.21	76.54	46.50
		$MS_{FxTxS(H)}$	15.11	15.70	16.72	15.49	14.91
		F[3]	10.50	5.71	6.89	4.94	3.11
		p	<0.01	<0.01	<0.01	<0.01	>0.05

[1] To determine differences across time of use for each fitting procedure and each HPD.

[2] U = UltraFit flanged plug; E = E-A-R foam plug.

[3] $$F = \frac{MS_T(df=2)}{MS_{FxTxS(H)}(df=72)};\quad F_{(.05,2,72)} = 3.13;\ F_{(.01,2,72)} = 4.94$$

Table 17. Results of Bonferroni *t*-Tests[1] for the Fitting Procedure-by-Time of Use-by-HPD (F x T x H) Interaction Post-hoc Analysis (Mean[2] Attenuation in dB)

Center Freq. (Hz)			125	250	500	1000	2000
CD[3]			4.3	4.4	4.5	4.3	4.3
HPD[4]	Fit	Time[5]					
U	Subject-Fit	W1	14.9 A	15.3 A	15.8 A	17.1 A	22.0 A
	Subject-Fit	W2	9.8 B	11.9 A	12.4 B	14.5 A	19.0 AB
	Subject-Fit	W3	4.5 C	5.7 B	7.4 C	9.7 B	16.9 B
U	Trained-Fit	W1	17.7 A	18.0 A	19.0 A	19.9 A	25.1 A
	Trained-Fit	W2	19.1 A	19.8 A	20.9 A	21.1 A	25.5 A
	Trained-Fit	W3	19.3 A	20.1 A	19.0 A	22.2 A	27.3 A
E	Subject-Fit	W1	17.0 A	17.8 A	19.8 A	19.4 A	29.5 A
	Subject-Fit	W2	10.6 B	10.2 B	12.8 B	13.9 B	23.2 B
	Subject-Fit	W3	13.5 AB	15.1 A	16.9 AB	16.9 AB	27.0 AB
E	Trained-Fit	W1	20.5 B	23.9 B	27.2 B	27.6 B	31.1 A
	Trained-Fit	W2	26.3 A	28.4 A	33.0 A	32.5 A	34.7 A
	Trained-Fit	W3	28.2 A	29.6 A	33.2 A	32.3 A	34.3 A

[1] Performed based only on the significant ($p < 0.05$) results found in simple effect *F*-tests from Table 16; the trained-fit UltraFit data were not analyzed using Bonferroni *t*-tests (mean data presented for only comparison purposes).

[2] Means (n = 10) within a table column with the different letter are significantly different at $p < 0.05$, according to Bonferroni *t*-tests which followed simple effect *F*-tests from Table 16.

Means (n = 10) within a table column with the same letter are not significantly different at $p < 0.05$, according to the results of simple effect *F*-tests from Table 16.

[3] Critical Difference $(CD) = t'_{\alpha}(c, df_{Error})\sqrt{\frac{2MS_{TxS(H)}}{n}}$

where $c = 3$, $df_{Error} = 72$, $n = 10$, $\alpha = 0.05$, and $t'_{0.05}(3, 72) = 2.46$

[4] U = UltraFit flanged plug; E = E-A-R foam plug.

[5] W1 = Week 1; W2 = Week 2; W3 = Week 3.

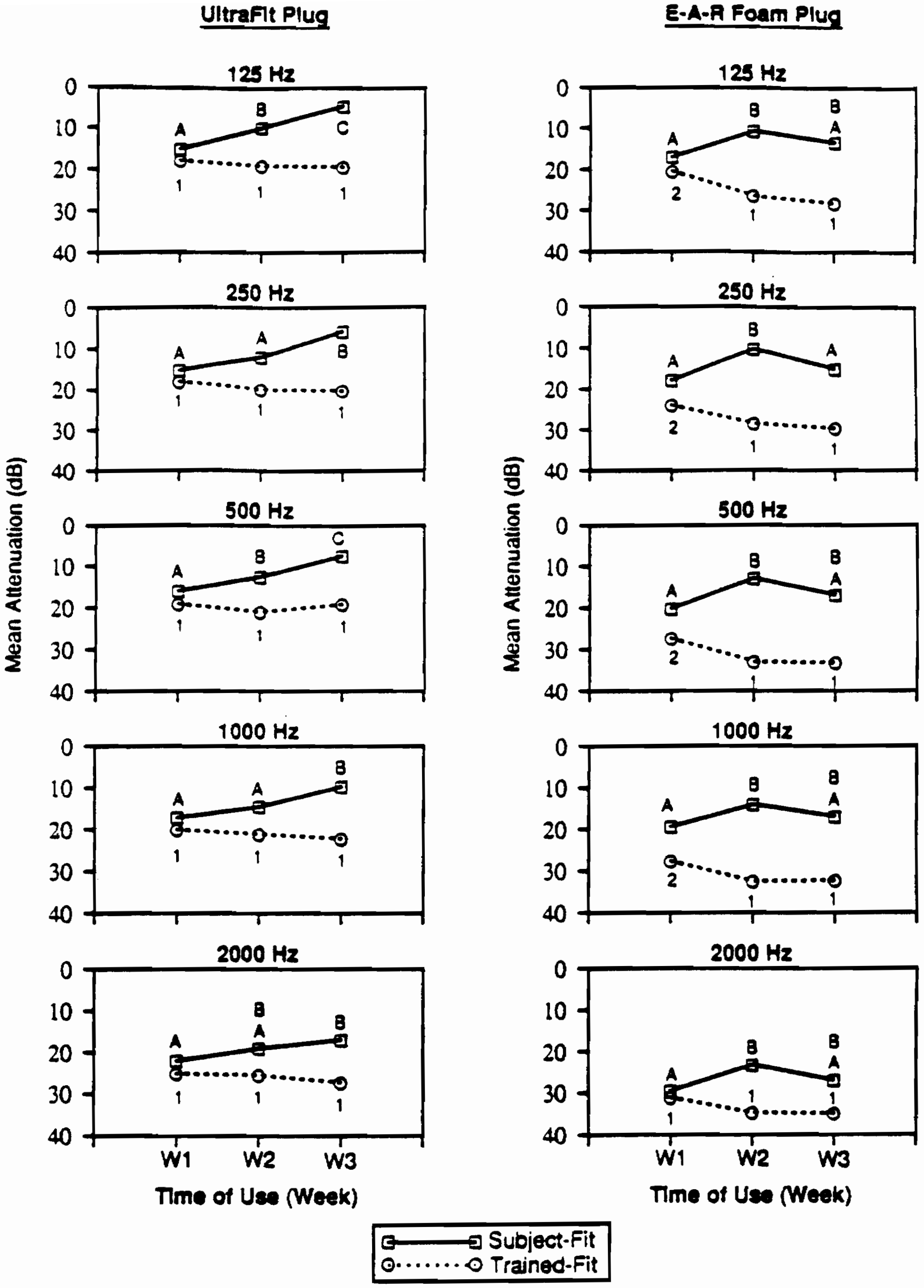


Figure 6. **1/3 octave-band field attenuation (in dB) over time under each fitting procedure for the UltraFit premolded and the E-A-R foam earplugs:** (Means with different letters [for the subject-fit] or numbers [for the trained-fit] are significantly different at $p < 0.05$).

discussed above.) From the simple effect *F*-tests to determine which fitting procedure had a significant effect over time, attenuation under subject-fit was found to change significantly ($p < 0.05$) over the 3-week period at frequencies of 2000 Hz and below (Table 18), while the time effect under trained-fit was slightly less consistent over the same frequency range. Scrutiny with the subsequent Bonferroni *t*-tests (Table 19) revealed a contrasting trend (Figure 7): slight attenuation *loss* (an average reduction of 2.8 dB over the 3-week period) occurred for the subject-fit condition, but slight attenuation *gain* (an average increase of 2.3 dB over the same period) was realized in the trained-fit condition across the frequencies of 2000 Hz and below. Figure 7 also illustrates that standard deviations (SDs) achieved with trained-fit were consistently lower than those obtained from the subject-fit over time. This is perhaps attributable to the more consistent fit which would be expected when subjects are trained in proper HPD placement.

Time of use-by-HPD interaction: This significant interaction implied that changes in achieved attenuation over the 3-week HPD usage period (collapsed across fitting procedures) were device-specific for the lower frequencies of 125 - 500 Hz. Simple effect *F*-tests (Table 20) were conducted on the time variable for each HPD. The results indicated that only the attenuation provided by the UltraFit plug changed significantly ($p < 0.05$) over the 3-week period at the low end ($\leq$ 500 Hz) of the frequency spectrum. For the UltraFit plug, Bonferroni *t*-tests were next employed, and the results are shown in Table 21 and Figure 8. Reductions in attenuation (an average loss of 4 dB across frequencies of 500 Hz and below) over the period were quite consistent for the UltraFit plug, and this occurred only in the subject-fit condition as discussed previously. However, this reduction did not occur for the other 3 HPDs.

Table 18. Simple Effect F-Test[1] Summary Table for the Fitting Procedure-by-Time of Use (F x T) Interaction Post-hoc Analysis (Attenuation in dB)

Center Freq. (Hz)		125	250	500	1000	2000
Fit	Statistics					
Subject-Fit	MS_T	178.89	138.68	104.03	62.68	57.40
	$MS_{FxTxS(H)}$	15.11	15.70	16.72	15.49	14.91
	F^2	11.84	8.83	6.22	4.05	3.85
	p	< 0.01	< 0.01	< 0.01	< 0.05	< 0.05
Trained-Fit	MS_T	77.39	75.33	92.21	55.36	41.30
	$MS_{FxTxS(H)}$	15.11	15.70	16.72	15.49	14.91
	F^3	5.12	4.80	5.51	3.57	2.77
	p	< 0.01	< 0.05	< 0.01	< 0.05	> 0.05

[1] To determine differences over time of use for each fitting procedure.

[2] $F = \frac{MS_T(df = 2)}{MS_{FxTxS(H)}(df = 72)}$; $F_{(.05,2,72)} = 3.13$; $F_{(.01,2,72)} = 4.94$

Table 19. Results of Bonferroni *t*-Test for the Fitting Procedure-by-Time of Use (F x T) Interaction Post-hoc Analysis (Mean[1] Attenuation in dB)

Center Freq. (Hz)		125	250	500	1000	2000
CD[2]		2.1	2.2	2.3	2.2	2.1
Fit	Time[3]					
Subject-Fit	W1	13.7 A	14.7 A	16.8 A	18.6 A	26.0 A
	W2	10.5 B	12.0 B	14.1 B	16.4 B	23.6 B
	W3	9.6 B	11.1 B	13.9 B	16.6 AB	24.6 AB
Trained-Fit	W1	15.8 B	17.7 B	20.1 B	22.3 B	28.5 A
	W2	18.1 A	19.7 A	22.9 A	24.1 A	29.2 A
	W3	18.4 A	20.3 A	22.4 A	24.4 A	30.5 A

[1] Means (n = 40) within a table column with the different letter are significantly different at $p < 0.05$.

[2] Critical Difference $(CD) = t'_{\alpha}(c, df_{Error})\sqrt{\frac{2MS_{T\times S(H)}}{n}}$

where $c = 3$, $df_{Error} = 72$, $n = 40$, $\alpha = 0.05$, and $t'_{0.05}(3, 72) = 2.46$

[3] W1 = Week 1; W2 = Week 2; W3 = Week 3.

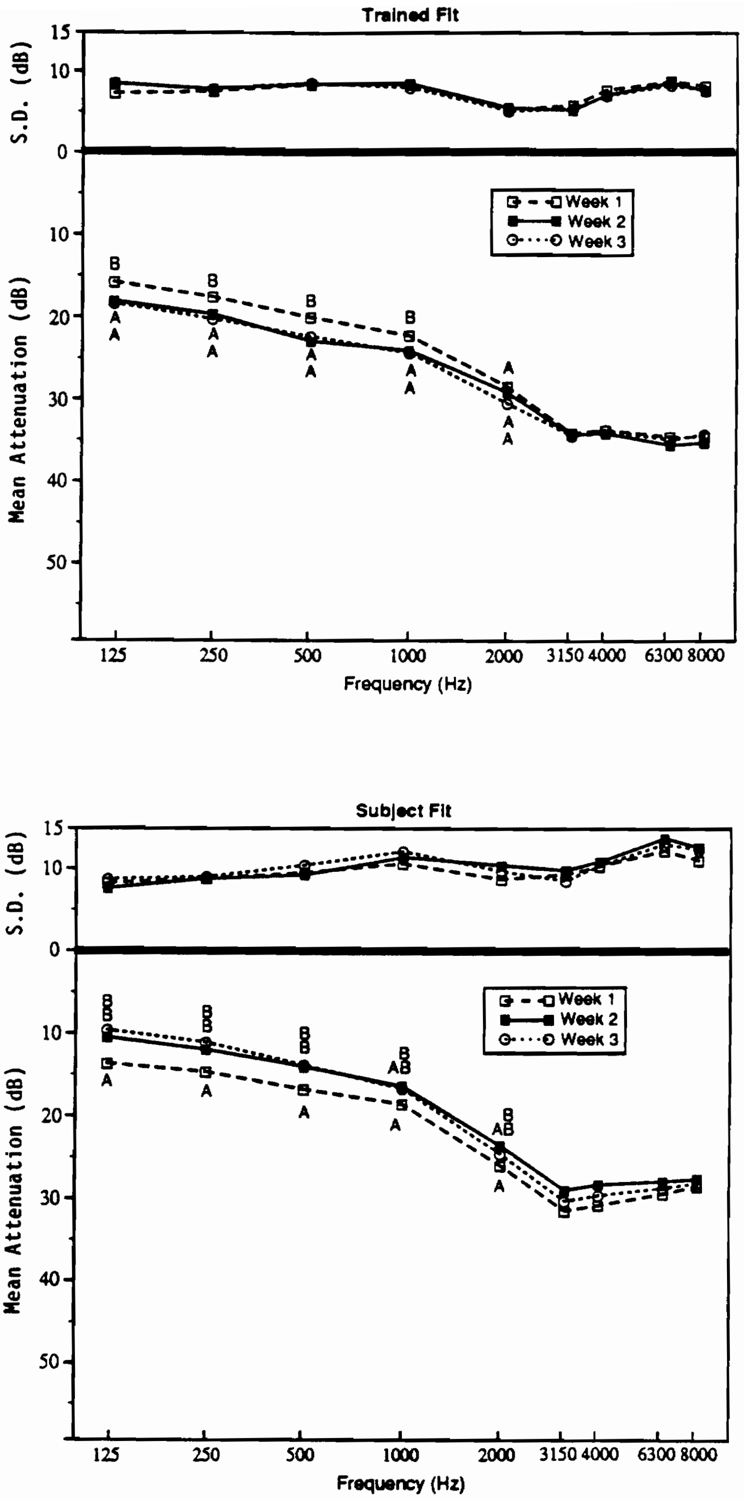


Figure 7. 1/3 octave-band field attenuation (in dB) over time under each fitting procedure: (Means with different letters in each frequency column are significantly different at $p < 0.05$).

Table 20. Simple Effect F-Test[1] Summary Table for Time of Use-by-HPD (T x H) Interaction Post-hoc Analysis (Attenuation in dB)

Center Freq. (Hz)		125	250	500
HPD[2]	Statistics			
U	MS_T	97.02	75.93	98.51
	$MS_{TxS(H)}$	13.09	14.43	17.82
	F^3	7.41	5.26	5.53
	p	<0.01	<0.01	<0.01
E	MS_T	32.56	44.16	24.15
	$MS_{TxS(H)}$	13.09	14.43	17.82
	F^3	2.49	3.06	1.36
	p	>0.05	>0.05	>0.05
B	MS_T	2.29	1.91	3.39
	$MS_{TxS(H)}$	13.09	14.43	17.82
	F^3	0.17	0.13	0.19
	p	>0.05	>0.05	>0.05
W	MS_T	5.95	0.93	12.57
	$MS_{TxS(H)}$	13.09	14.43	17.82
	F^3	0.45	0.06	0.71
	p	>0.05	>0.05	>0.05

[1] To determine differences across time of use for each HPD.

[2] U = UltraFit flanged plug; E = E-A-R foam plug; B = Bilsom muff; W = Willson canal cap.

[3] $F = \frac{MS_T(df=2)}{MS_{TxS(H)}(df=72)}$; $F_{(.05,2,72)} = 3.13$; $F_{(.01,2,72)} = 4.94$

Table 21. Results of Bonferroni *t*-Test[1] for the Time of Use-by-HPD (T x H) Interaction Post-hoc Analysis (Mean[2] Attenuation in dB)

Center Freq. (Hz)		125	250	500
CD[3]		2.81	2.97	3.28
HPD[4]	Time[5]			
U	W1	16.28 A	16.62 A	17.37 A
	W2	14.40 A B	15.86 A B	16.60 A
	W3	11.89 B	12.93 B	13.20 B
E	W1	18.74 A	20.84 A	23.48 A
	W2	18.48 A	19.28 A	22.92 A
	W3	20.81 A	22.23 A	25.04 A
B	W1	9.25 A	12.89 A	19.98 A
	W2	8.68 A	13.43 A	20.65 A
	W3	8.65 A	12.90 A	19.89 A
W	W1	14.65 A	14.28 A	12.88 A
	W2	15.58 A	14.70 A	13.90 A
	W3	14.61 A	14.54 A	14.44 A

[1] Only these results for the UltraFit plug were analyzed using Bonferroni *t*-test, because other HPDs were not found to be sensitive to time of use effects in simple effect *F*-test from Table 20 (mean data presented for only comparison purposes).

[2] Means (n = 20) within a table column with the different letter are significantly different at $p < 0.05$, according to Bonferroni *t*-tests which followed simple effect *F*-tests from Table 20.

Means (n = 20) within a table column with the same letter are not significantly different at $p < 0.05$, according to the results of simple effect *F*-test from Table 20.

[3] Critical Difference $(CD) = t'_{\alpha}(c, df_{Error})\sqrt{\frac{2MS_{TxS(H)}}{n}}$

where $c = 3$, $df_{Error} = 72$, $n = 20$, $\alpha = 0.05$, and $t'_{0.05}(3, 72) = 2.46$

[4] U = UltraFit flanged plug; E = E-A-R foam plug; B = Bilsom muff; W = Willson canal cap.

[5] W1 = Week 1; W2 = Week 2; W3 = Week 3.

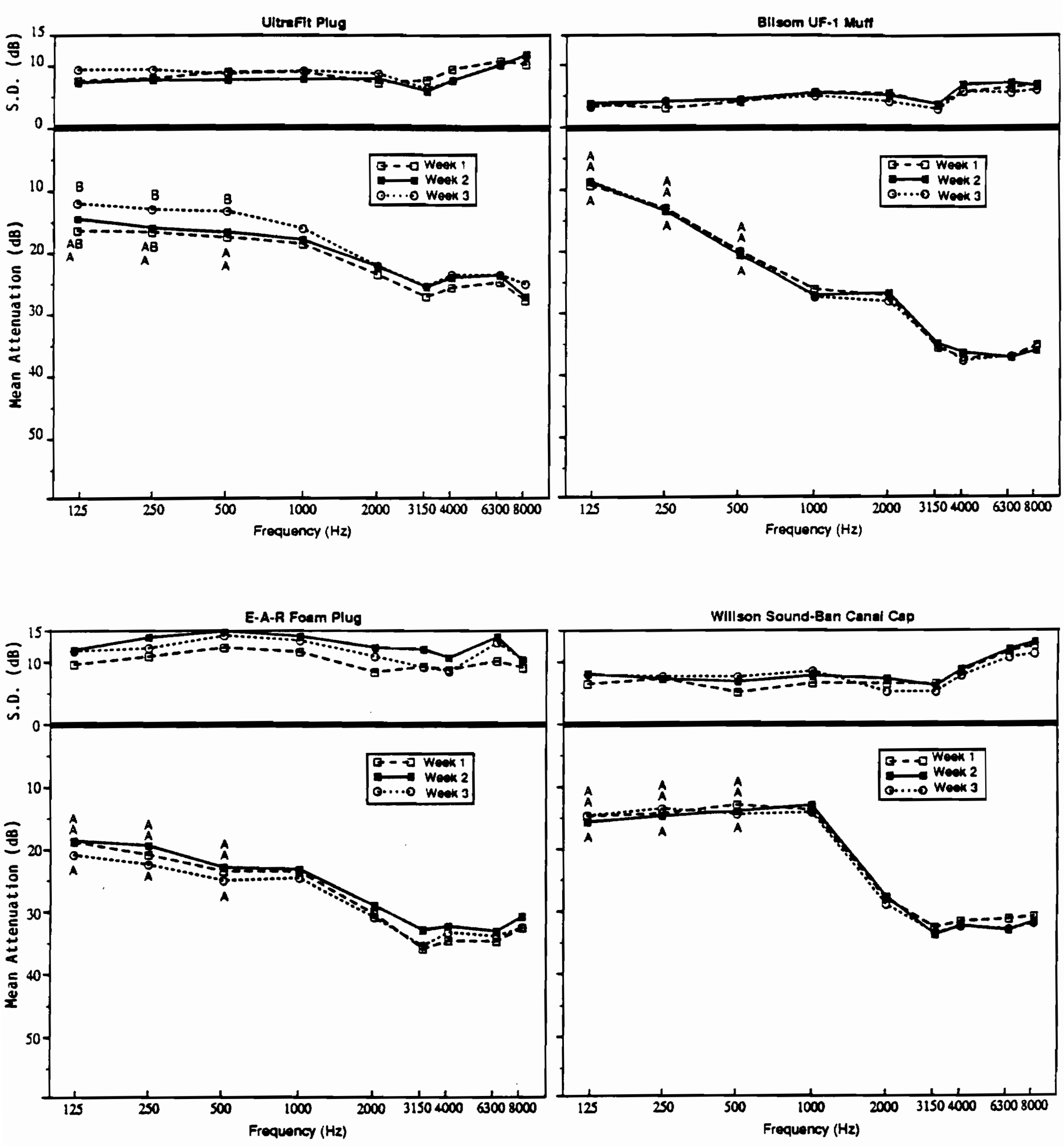


Figure 8. 1/3 octave-band field attenuation (in dB) for each HPD over time: (Means with different letters in each frequency column are significantly different at $p < 0.05$).

Fitting procedure-by-HPD interaction: The significant ($p < 0.01$) fitting procedure-by-HPD (F x H) interaction effects indicated that the influence of fitting procedure on HPD attenuation was also highly device-dependent, as corroborated by the results of the earlier laboratory study (Casali and Park, 1990a). Simple effect *F*-tests were performed to examine the difference between the 2 fitting procedures for each HPD (Table 22). Both earplugs were found to be highly sensitive to the fitting procedure effect, whereas the ear canal cap and earmuff were not. Comparisons of mean attenuation values for the earplugs (Table 23) revealed consistently improved attenuation in the trained-fit condition over the subject-fit condition, with a particularly pronounced low frequency benefit for the user-molded foam earplug, as illustrated in Figure 9. The lowest and highest attenuation improvements due to training were 7.2 dB at 1000 Hz and 13.2 dB at 8000 Hz, respectively for the UltraFit plug; and 8.7 dB at 8000 Hz and 14.6 dB at 500 Hz, respectively for the E-A-R foam plug. Also, for all devices, SDs for the trained-fit condition were again considerably smaller than those under subject-fit. These interaction results, as well as the main effect of fitting procedure (to be discussed), clearly demonstrate the importance of training workers in proper fitting of earplugs to improve workplace protection levels.

HPD main effect: With the data collapsed across the other factors, the significant main effect of HPD was expected because it is well known that different HPDs provide a wide range of protection levels. Newman-Keuls Sequential Range tests were performed on the HPD main effect (Table 24) in order to isolate average attenuation provided by the 4 types of HPDs, and attenuation differences between HPDs are shown in Figure 10. The insert protectors, especially the E-A-R foam plug, generally offered higher attenuation at lower frequencies than the muff (e.g., the foam plug had a maximum attenuation benefit of 10.4 dB over the muff at 500 Hz and below).

Table 22. Simple Effect *F*-Test[1] Summary Table for the Fitting Procedure-by-HPD (F x H) Interaction Post-hoc Analysis (Attenuation in dB)

Center Freq. (Hz)		125	250	500	1000	6300	8000
HPD[2]	Statistics						
U	MS_F	1211.85	1048.34	906.76	794.98	2247.26	2639.40
	$MS_{FxS(H)}$	51.37	49.22	52.61	58.98	100.26	94.37
	F[3]	23.59	21.30	17.24	13.48	22.41	27.97
	p	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
E	MS_F	1925.53	2514.24	3203.24	2959.63	1562.64	1131.44
	$MS_{FxS(H)}$	51.37	49.22	52.61	58.98	100.26	94.37
	F[3]	37.48	51.08	60.89	50.18	15.58	11.99
	p	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
B	MS_F	15.81	41.33	43.27	9.40	8.66	9.13
	$MS_{FxS(H)}$	51.37	49.22	52.61	58.98	100.26	94.37
	F[3]	0.31	0.83	0.82	0.16	0.09	0.10
	p	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
W	MS_F	158.60	183.23	156.66	190.28	94.00	221.38
	$MS_{FxS(H)}$	51.37	49.22	52.61	58.98	100.26	94.37
	F[3]	3.09	3.72	2.98	3.23	0.94	2.35
	p	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05

[1] To determine the difference in fitting procedure for each HPD.

[2] U = UltraFit flanged plug; E = E-A-R foam plug; B = Bilsom muff; W = Willson canal cap.

[3] $F = \dfrac{MS_F(df = 1)}{MS_{FxS(H)}(df = 36)}$; $F_{(.05,\,1,\,36)} = 4.12$; $F_{(.01,\,1,\,36)} = 7.41$

Table 23. Mean[1] Attenuation (in dB) Comparison for the Fitting Procedure-by-HPD (F x H) Interaction Post-hoc Analysis

Center Freq. (Hz)		125	250	500	1000	6300	8000
HPD[2]	Fit Condition						
U	Trained-Fit	18.7 A	19.3 A	19.6 A	21.0 A	30.1 A	33.2 A
	Subject-Fit	9.7 B	11.0 B	11.8 B	13.8 B	17.8 B	20.0 B
E	Trained-Fit	25.0 A	27.3 A	31.1 A	30.8 A	39.0 A	36.3 A
	Subject-Fit	13.7 B	14.4 B	16.5 B	16.7 B	28.8 B	27.6 B
B	Trained-Fit	9.4 A	13.9 A	21.0 A	27.3 A	27.6 A	36.0 A
	Subject-Fit	8.3 A	12.2 A	19.3 A	26.5 A	36.8 A	35.3 A
W	Trained-Fit	16.6 A	16.3 A	15.4 A	15.3 A	33.6 A	33.3 A
	Subject-Fit	13.3 A	12.8 A	12.1 A	11.8 A	31.1 A	29.5 A

[1] Means (n = 30) within a table column with the different letter are significantly different at $p < 0.05$, according to the results of simple effect *F*-test from Table 22.

[2] U = UltraFit flanged plug; E = E-A-R foam plug; B = Bilsom muff; W = Willson canal cap.

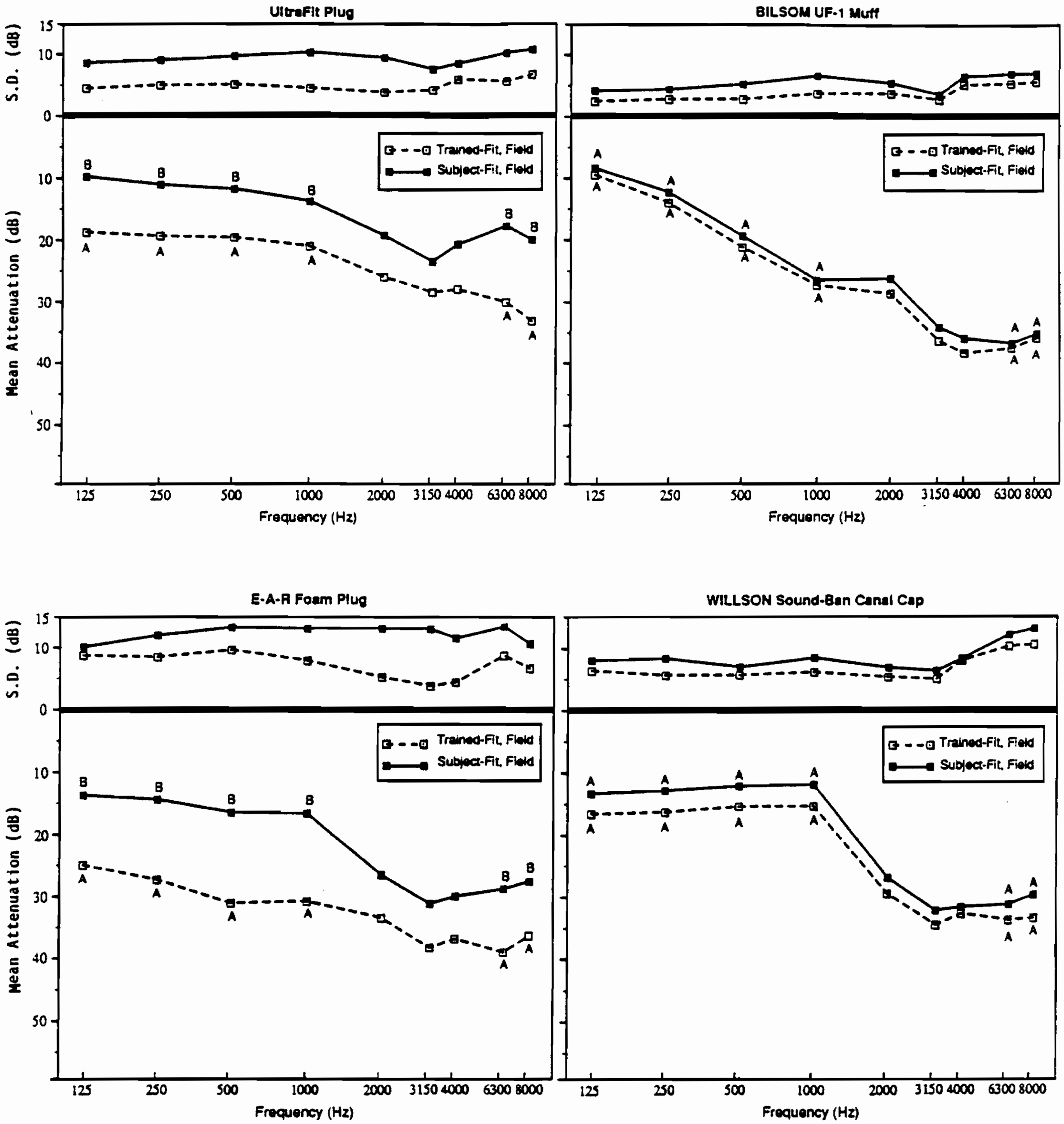


Figure 9. **1/3 octave-band field attenuation (in dB) for each HPD under each fitting procedure:** (Means with different letters in each frequency column are significantly different at $p < 0.05$).

Table 24. **Results of Newman-Keuls Test for the HPD Main Effect Post-hoc Analysis (Mean[1] Attenuation in dB; Standard Deviations also Shown in Parentheses)**

Center Frequency (Hz)	125	250	500	1000	2000	3150	4000	6300	8000
HPD[2]									
E	19.3 A (11.0)	20.8 A (12.2)	23.8 A (13.7)	23.8 A (12.9)	30.1 A (10.5)	34.7 A (10.1)	33.4 A (9.3)	33.9 A (12.4)	31.9 A (9.8)
U	14.2 AB (8.2)	15.1 AB (8.4)	15.7 B (8.6)	17.4 B (8.7)	22.6 B (7.8)	26.0 B (6.6)	24.4 B (8.2)	23.9 B (10.3)	26.6 A (11.2)
W	14.9 AB (7.4)	14.5 AB (7.3)	13.7 B (6.5)	13.6 B (7.6)	28.1 AB (6.3)	33.3 A (5.9)	32.1 A (8.2)	32.3 A (11.3)	31.4 A (12.2)
B	8.9 B (3.5)	13.1 B (3.8)	20.2 AB (4.2)	26.9 A (5.3)	27.4 AB (4.9)	35.3 A (3.4)	37.2 A (6.0)	37.2 A (6.2)	35.6 A (6.3)

[1] Means (n = 60) within a table column with the different letter are significantly different at $p < 0.05$, according to the ANOVA results from Tables 6 to 14.

[2] E = E-A-R foam plug; U = UltraFit flanged plug; W = Willson canal cap; B = Bilsom muff.

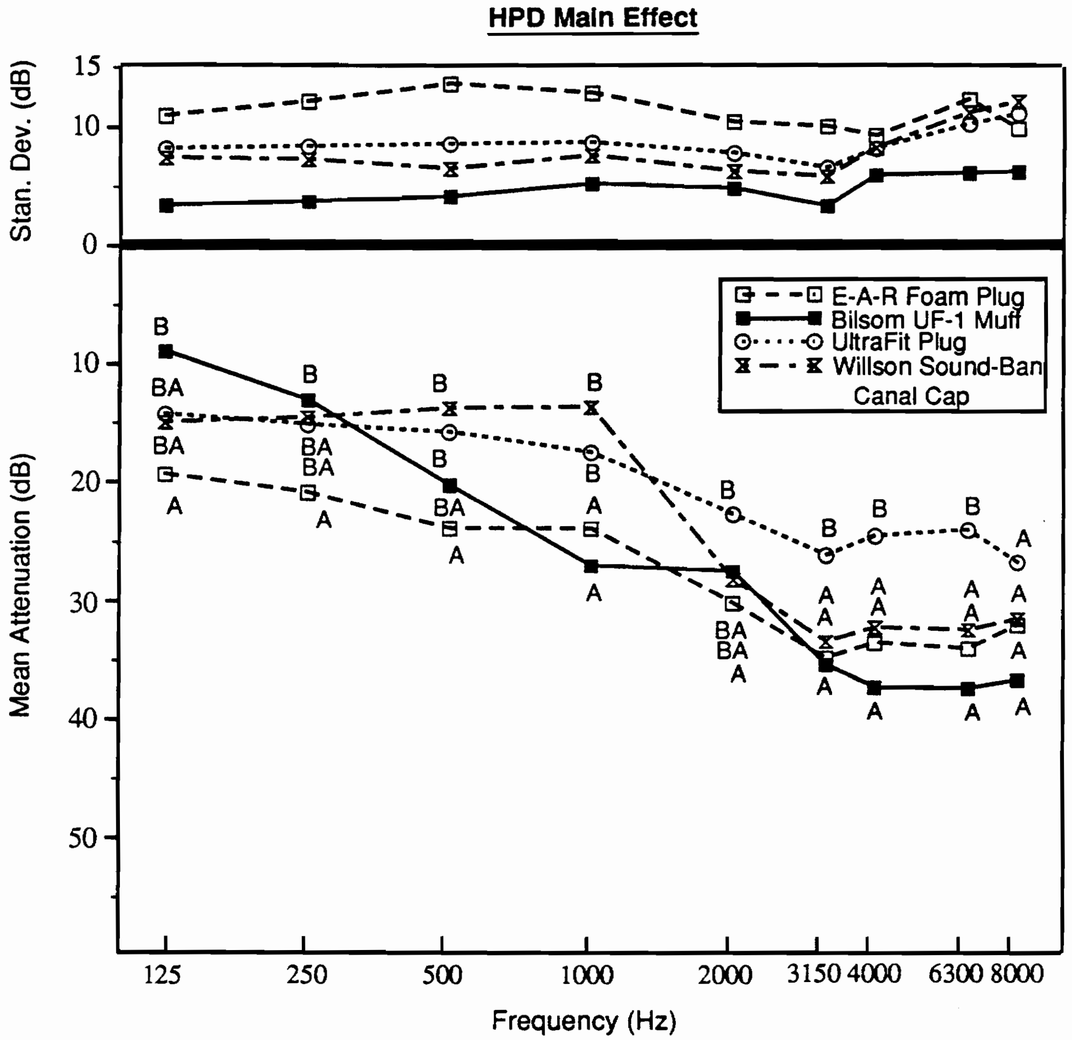


Figure 10. **1/3 octave-band field attenuation (in dB) for each HPD:** (Means with different letters in each frequency column are significantly different at $p < 0.05$).

However, this was not true at frequencies above 3150 Hz, where the muff exhibited the highest attenuation. This result was anticipated due to differences in the physical characteristics between inserts and muffs and to the manner in which each interfaces to the ear canal/head. For example, the level of stiffness and effective mass of earplugs, resulting largely from the earplugs' contact with the ear canal walls, may provide more influence on low frequency (e.g., 1000 Hz or below) attenuation than that achieved at high frequencies (Zwislocki, 1957), whereas more consistent acoustical resistance with optimum cavity damping of the cup component of earmuffs at high frequencies (e.g., 2000 Hz or above) provides high frequency attenuation benefits for earmuffs (Shaw, 1982). Figure 10 further shows that the largest and the smallest SDs were achieved with the foam plug and the muff, respectively. One possible speculative interpretation of this result is that the muff is most straightforward to fit and therefore produces less variable attenuation across conditions, while the foam plug is the most complex, thereby producing more variable results under different field conditions.

Fitting procedure main effect: Attenuation achieved under the 2 fitting procedures was significantly different ($p < 0.01$) at all test frequencies. The mean attenuation comparison (Table 25 and Figure 11) showed that the trained-fit condition provided consistently more attenuation (4 to 7 dB, depending on the frequency) than the subject-fit condition, which was also borne out in the fitting procedure-by-HPD interaction discussed earlier. Even brief training to achieve better fitting can markedly improve the noise protection obtained, at least for the earplugs tested in this study. Also, consistently smaller SDs across frequency were obtained in the trained-fit than in the subject-fit condition, attesting to the more uniform fit produced under training (Table 25).

Table 25. Mean[1] Attenuation (in dB) Comparison (Standard Deviations Shown in Parentheses) for the Fitting Procedure Main Effect

Center Frequency (Hz)	125	250	500	1000	2000	3150	4000	6300	8000
Fit Condition									
Trained-Fit	17.4 A (8.2)	19.2 A (7.7)	21.8 A (8.5)	23.6 A (8.3)	29.4 A (5.3)	34.4 A (5.5)	34.0 A (7.2)	35.1 A (8.5)	34.7 A (7.7)
Subject-Fit	11.3 B (8.3)	12.6 B (8.9)	14.9 B (9.7)	17.2 B (11.3)	24.7 B (9.6)	30.3 B (9.2)	29.6 B (10.5)	28.6 B (12.9)	28.1 B (11.9)

[1] Means (n = 120) within a table column with the different letter are significantly different at $p < 0.05$, according to the ANOVA results from Tables 6 to 14.

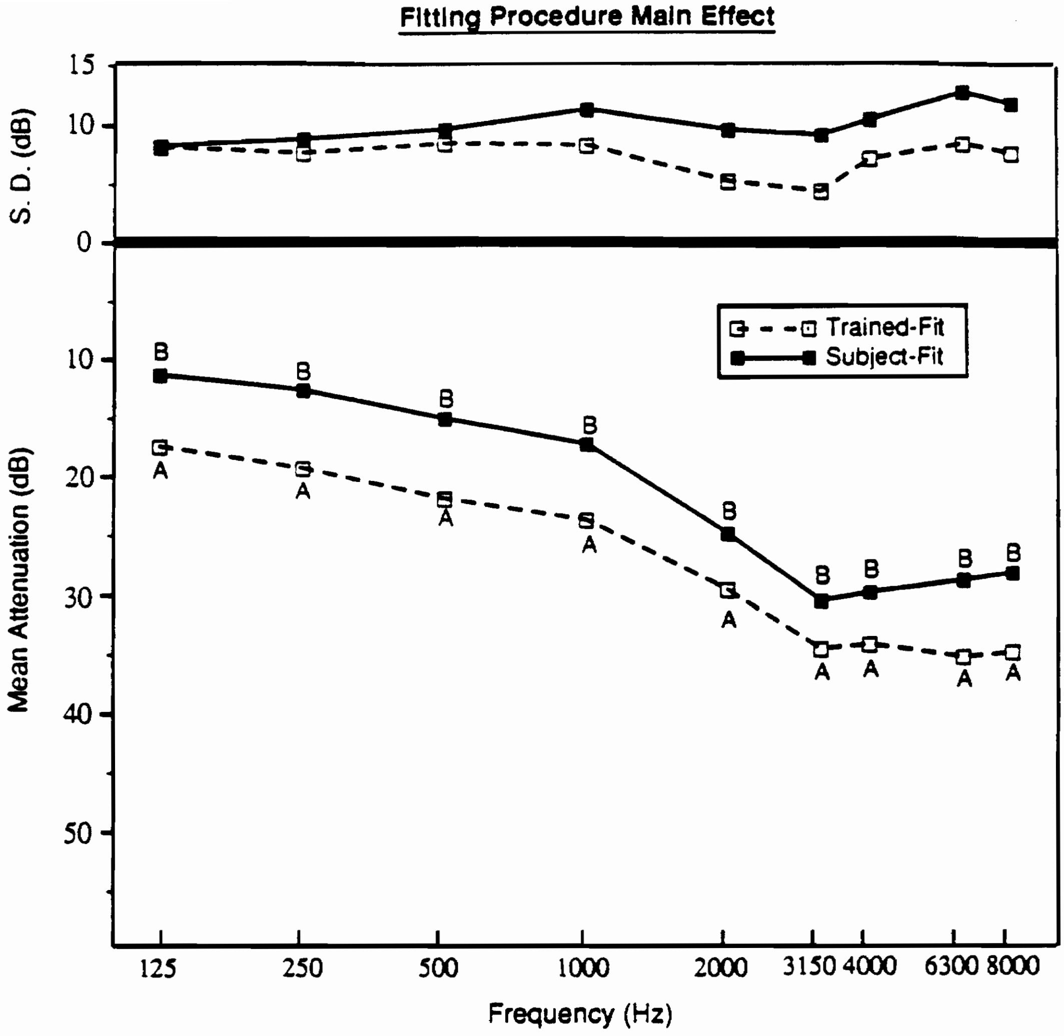


Figure 11. 1/3 octave-band field attenuation (in dB) for each fitting procedure: (Means with different letters in each frequency column are significantly different at $p < 0.05$).

Noise Reduction Rating (NRR) Data Analysis

As discussed earlier in the "RATING HPD ATTENUATION" section, the EPA-required (EPA, 1990) Noise Reduction Rating (NRR) is currently the most common single-number rating (in the United States) for reflecting broadband HPD attenuation across a frequency spectrum. The NRR, as previously defined, is the difference between the overall C-weighted sound level of a pink noise spectrum and the A-weighted noise levels reaching the wearer's ear when the HPD in question is donned. Thus, the wearer's exposure level (in dBA) can be estimated by the workplace noise level (in dBC) subtracted by NRR. If the NRR is chosen to be subtracted from A-weighted sound levels, an additional 7 dB safety factor, which accounts for the largest differences expected between the C- and the A-weighted sound levels of workplace noise, needs to be included in the computation of the wearer's estimated exposure level. That is, the exposure level at the wearer's ear can be estimated by the workplace noise level (in dBA) subtracted by "NRR-7 dB" (OSHA, 1983a). In practice, the NRR is very important to manufacturers, buyers, and end-users of HPDs. Using the 3 sets of spectral attenuation data obtained from 10 subjects (i.e., 30 attenuation scores at each of the 9 test frequencies for 10 subjects) on each HPD (as per ANSI S12.6-1984), NRRs for each fitting condition were calculated.

Calculation of field NRR scores: For a more realistic estimation of real-world NRR, "NRR_{84}" scores were computed using a 1-standard deviation (SD) correction, as explained previously. NRR_{84} is an approximate estimate of minimum protection for 84% of the HPD wearer population. The computed NRR_{84} and typical NRR (i.e.,

NRR_{98}) values are presented in Table 26, along with manufacturers' reported NRR (and computed manufacturers' NRR_{84}) values for comparison.

As evidenced in both field NRR_{84} and field NRR_{98} (standard NRR) results (Table 26), trained fitting of any of the HPDs (which yielded the highest field attenuation) provided substantially lower noise reduction values than the manufacturers' labeled ratings: the discrepancy ranged from 5 to 10 dB and from 8 to 16 dB when each of the field NRR_{84} and the field NRR_{98} scores was compared with the manufacturers' NRRs, respectively. When subject-fit (perhaps the most realistic and typical industrial field condition) was used, overestimation of protection by the manufacturers' NRRs was much worse: discrepancies of 9 to 23 dB and 14 to 36 dB resulted from the comparison of manufacturers' NRRs with the field NRR_{84} and the field NRR_{98}, respectively. Clearly, the manufacturers' NRRs (and, of course, the manufacturers' computed NRR_{84}) grossly overestimate the typical protection performance which is achieved in the industrial workplace.

Prediction of Field NRR from Single-Frequency Data

Although spectral data from the 9 test frequencies (i.e., 9 1/3-octave bands), obtained as per ANSI S12.6-1984 or ANSI S3.19-1974, are required to compute the overall broadband attenuation (i.e., NRR) of an HPD, it is probably not necessary to have all of that information in order to gain a quick estimate of the HPD's overall attenuation performance. As suggested by a few researchers (e.g., Berger, 1988c; Fleming, 1980; Padilla, 1976), single-frequency or single 1/3-octave band attenuation data might be used to predict the overall (broadband) noise protection provided by the HPD. Preliminary results from prior research have shown that 500 or 1000 Hz data are most promising in this regard. The rationale for this approach is that if field

Table 26. Field versus Manufacturer-Reported NRR Scores (in dB)

HPD[6]	S-F[1] [NRR$_{84}$[4]]	T-F[1] [NRR$_{84}$[4]]	S-F[1] [NRR[5]]	T-F[1] [NRR[5]]	Mfgr's[2] [NRR[5]]	Mfgr's[3] [NRR$_{84}$[4]]
U	4.3	17.0	-5.6	12.2	27.0	31.1
E	5.6	23.3	-7.4	15.2	29.0	33.7
B	16.2	19.7	11.0	16.6	25.0	27.3
W	6.4	11.9	-1.9	5.8	22.0	23.9

[1] S-F = Subject-Fit; T-F = Trained-Fit

[2] Mfgr's = Manufacturer's: Manufacturer-reported NRR at time of study.

[3] Mfgr's = Manufacturer's: NRR$_{84}$ calculated on the basis of the spectral data (mean and standard deviation) reported by the manufacturer.

[4] Incorporates a 1 standard deviation correction for an approximate of protection for 84% of the user population.

[5] Incorporates a 2 standard deviation correction for an approximate of protection for 98% of the user population.

[6] U = UltraFit flanged plug; E = E-A-R foam plug; B = Bilsom muff; W = Willson canal cap

attenuation measurements could be limited to only one test band (or pure-tone frequency), this would save considerable amounts of time in field HPD testing and also provide a much simpler testing procedure. Thus, actual protection levels that individual workers are realizing on the job could be quickly checked during the required annual audiometric check-up. If the worker is not properly sized or fit, the acoustic attenuation test should be sensitive to this fact so that different devices can be supplied and/or the worker trained in correct placement.

Regression analysis

Simple linear regression was applied in an approach to predict the single-number field protection, termed NRR_{PS} (NRR Per Subject), from attenuation measurements at 500 Hz (namely, AT500) or at 1000 Hz (namely, AT1000). This modified NRR, the NRR_{PS}, is simply an NRR with no standard deviation corrections (because standard deviation correction is not possible with a single subject), but including the 3 dB spectral uncertainty reduction (EPA, 1990). Thus, the NRR_{PS} cannot be substituted on an exact basis for the "standard" NRR (i.e., NRR_{98}), which includes a 2 standard deviation correction, but it is still a useful broadband single-number attenuation metric. The NRR_{PS} was computed for each subject so that each observation in each experimental cell had a one-to-one relationship with each single 1/3-octave test band (hereafter single-frequency) attenuation data point at 500 Hz or 1000 Hz.

Using the AT500/AT1000 field attenuation and computed NRR_{PS} values, 2 regression lines ("NRR_{PS} on AT500" and "NRR_{PS} on AT1000") were first constructed for data collapsed across HPD, and the regression results are summarized in Table 27 in terms of slope, intercept, and Pearson correlation coefficient (each denoted by "*a*," "*b*," and "*r*," respectively). A reference line with a slope of 1 and intercept of 0 was used for prediction performance comparison purposes. The results from Table 27 show that overall, AT500 and AT1000 provided nearly equally accurate predictions of NRR_{PS}, based on the descriptive regression statistics of slope, intercept, and correlation coefficient values (the results of statistical significance tests were also identical for both cases: significant results for testing the null hypotheses of a slope equal to 1.0 and an intercept equal to 0 were rejected at $p < 0.05$). AT500 was a negligibly better predictor of NRR_{PS} for the subject-fit data (i.e., the regression line was closer to the reference line with a slightly greater correlation coefficient value) than AT1000, though again both AT500 and AT1000 revealed all statistically significant results for testing the aforementioned hypotheses. Also, according to Berger (1989), assuming that all else is constant, the 500 Hz frequency may offer a slight advantage over 1000 Hz if only a single-frequency is used due to its better prediction (in his results) of attenuation at the low end of the frequency spectrum (i.e., 125 Hz), where attenuation is usually at a minimum. But because the results in this study exhibited no clear advantage of either frequency, further regression analyses addressed both AT500 and AT1000.

For each HPD and each set of the partitioned-data (i.e., partitioned with respect to fitting procedure, including subject-fit, trained-fit, and overall data), regression analyses were made of "NRR_{PS} on AT500" and "NRR_{PS} on AT1000," and the resultant statistics are presented in Tables 28 and 29 (for AT500 and AT1000 analyses, respectively) and also illustrated in Figures 12 through 15 for AT500 results and Figures 16 through 19 for AT1000 results, respectively (refer to the regression versus the reference lines; prediction intervals in these figures will be discussed later). As evidenced in these tables and figures, both AT500 and AT1000 yielded very similar prediction results for all HPDs except the Bilsom muff. For the Bilsom muff, AT500

Table 27. Single 1/3-Octave Band Prediction of NRR_{PS} Regression Statistics[1] for Data Collapsed across HPD

REGRESSION	FIT	*a*	*b*	*r*
NRR_{PS} on AT500[2]	Overall	0.78	4.66	0.92
NRR_{PS} on AT500	Subject-Fit	0.92	2.52	0.97
NRR_{PS} on AT500	Trained-Fit	0.60	8.87	0.83
NRR_{PS} on AT1000[3]	Overall	0.73	4.11	0.92
NRR_{PS} on AT1000	Subject-Fit	0.77	3.04	0.95
NRR_{PS} on AT1000	Trained-Fit	0.62	7.17	0.84

[1] Reference line for regression comparisons is the one with slope (*a*) of 1 and intercept (*b*) of 0.

[2] $NRR_{PS} = a * AT500 + b$

[3] $NRR_{PS} = a * AT1000 + b$

Table 28. Single 1/3-Octave Band Prediction of NRR_{PS} Regression Statistics[1] Using 500 Hz Attenuation Data for Each HPD and Each Fitting Procedure

REGRESSION	HPD[2]	FIT	*a*	*b*	*r*
NRR_{PS} on AT500[3]	E	Overall	0.74	4.60	0.90
NRR_{PS} on AT500	E	Subject-Fit	0.92	2.40	0.98
NRR_{PS} on AT500	E	Trained-Fit	0.52	10.56	0.65
NRR_{PS} on AT500	B	Overall	0.82	5.00	0.92
NRR_{PS} on AT500	B	Subject-Fit	0.85	4.26	0.96
NRR_{PS} on AT500	B	Trained-Fit	0.68	8.03	0.77
NRR_{PS} on AT500	U	Overall	0.89	2.98	0.96
NRR_{PS} on AT500	U	Subject-Fit	0.90	2.35	0.96
NRR_{PS} on AT500	U	Trained-Fit	0.69	7.40	0.93
NRR_{PS} on AT500	W	Overall	0.88	3.32	0.91
NRR_{PS} on AT500	W	Subject-Fit	0.92	2.52	0.92
NRR_{PS} on AT500	W	Trained-Fit	0.79	5.08	0.89

[1] Reference line for regression comparisons is the one with slope (*a*) of 1 and intercept (*b*) of 0.

[2] E = E-A-R foam plug; B = Bilsom muff; U = UltraFit flanged plug; W = Willson canal cap.

[3] $NRR_{PS} = a * AT500 + b$

Table 29. Single 1/3-Octave Band Prediction of NRR_{PS} Regression Statistics[1] Using 1000 Hz Attenuation Data for Each HPD and Each Fitting Procedure

REGRESSION	HPD[2]	FIT	*a*	*b*	*r*
NRR_{PS} on AT1000[3]	E	Overall	0.80	3.20	0.91
NRR_{PS} on AT1000	E	Subject-Fit	0.94	1.85	0.99
NRR_{PS} on AT1000	E	Trained-Fit	0.65	6.89	0.67
NRR_{PS} on AT1000	B	Overall	0.59	5.76	0.84
NRR_{PS} on AT1000	B	Subject-Fit	0.60	4.89	0.86
NRR_{PS} on AT1000	B	Trained-Fit	0.52	8.18	0.79
NRR_{PS} on AT1000	U	Overall	0.89	1.59	0.97
NRR_{PS} on AT1000	U	Subject-Fit	0.85	1.23	0.97
NRR_{PS} on AT1000	U	Trained-Fit	0.76	5.06	0.90
NRR_{PS} on AT1000	W	Overall	0.81	4.51	0.97
NRR_{PS} on AT1000	W	Subject-Fit	0.80	4.30	0.97
NRR_{PS} on AT1000	W	Trained-Fit	0.79	5.05	0.96

[1] Reference line for regression comparisons is the one with slope (*a*) of 1 and intercept (*b*) of 0.

[2] E = E-A-R foam plug; B = Bilsom muff; U = UltraFit flanged plug; W = Willson canal cap.

[3] $NRR_{PS} = a * AT1000 + b$

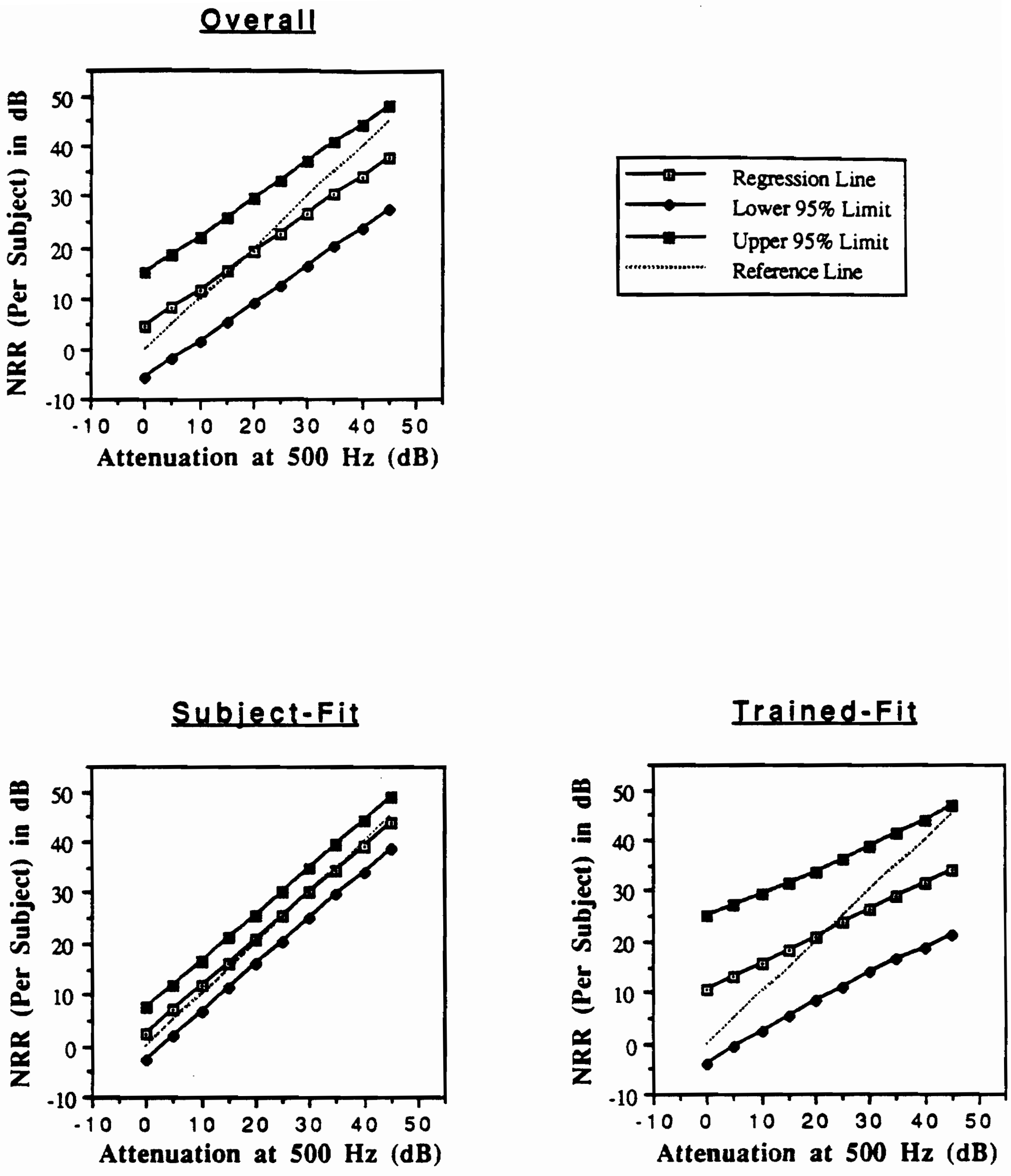


Figure 12. **Prediction of field NRR$_{PS}$ from single 1/3-octave band (500 Hz) attenuation measurements for the E-A-R foam plug:** (Regression line and prediction interval for each fitting procedure; intercept values are correct when single band attenuation equals to 0).

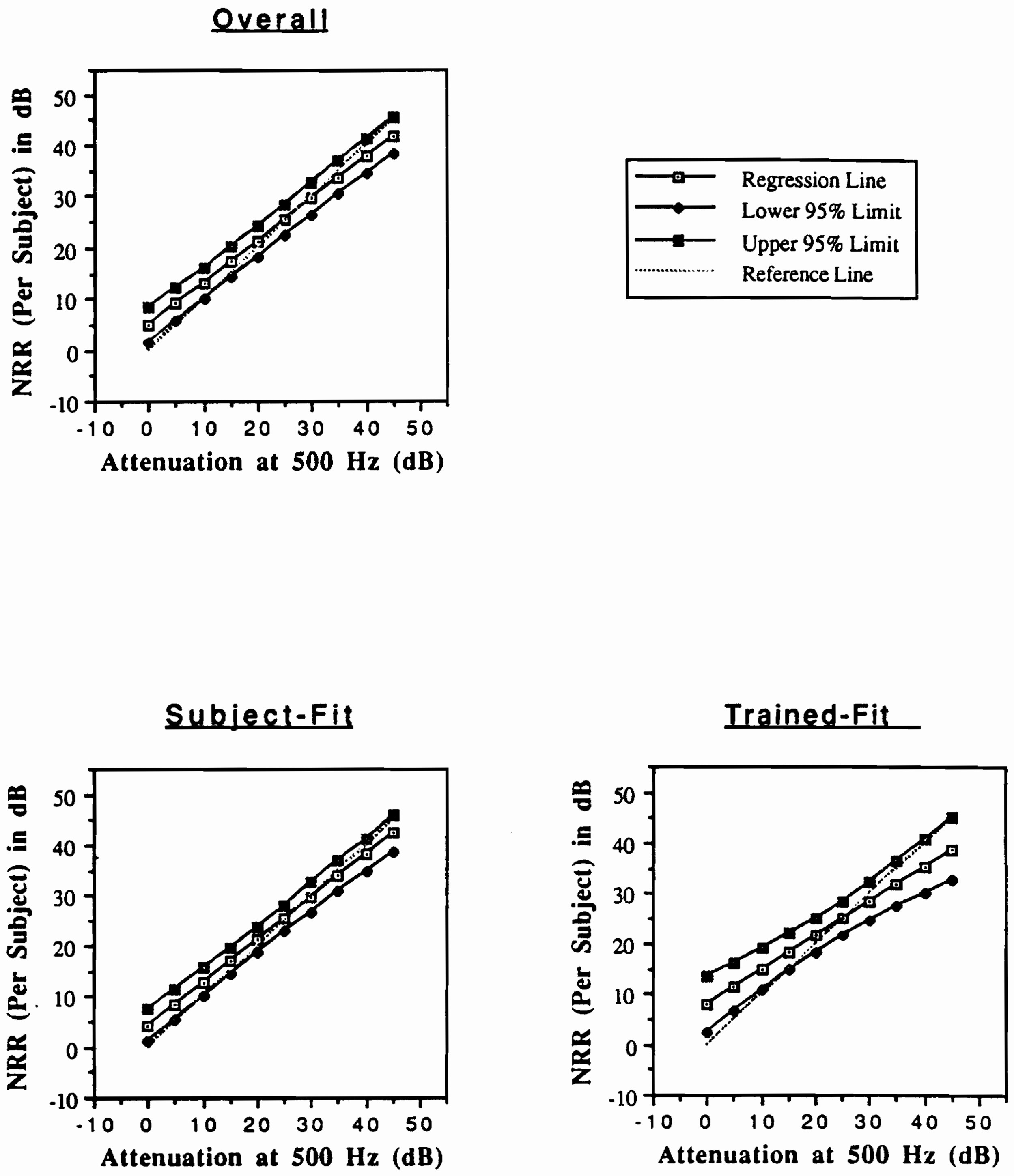


Figure 13. **Prediction of field NRR_{PS} from single 1/3-octave band (500 Hz) attenuation measurements for the Bilsom UF-1 muff:** (Regression line and prediction interval for each fitting procedure; intercept values are correct when single band attenuation equals to 0).

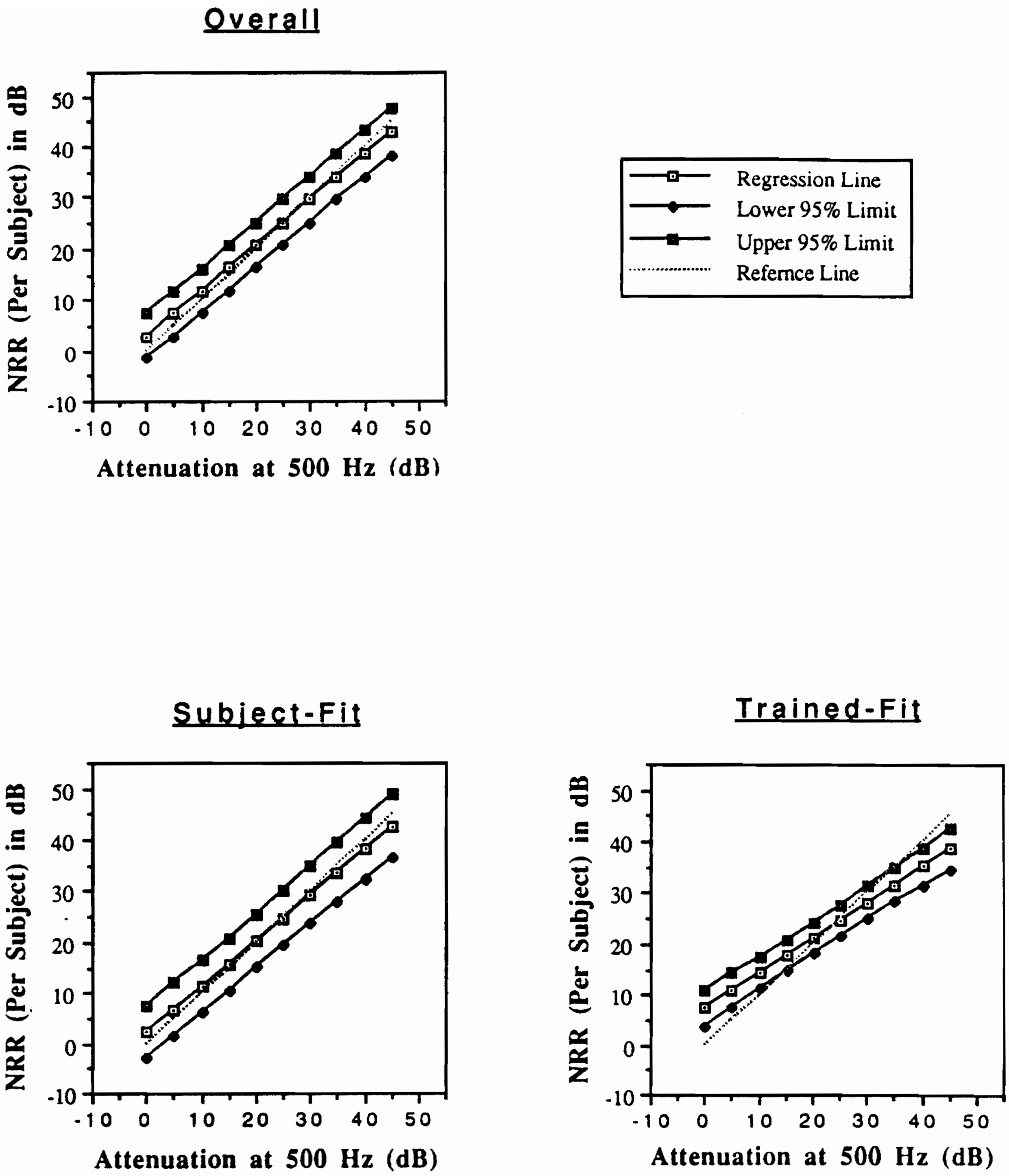


Figure 14. Prediction of field NRR$_{PS}$ from single 1/3-octave band (500 Hz) attenuation measurements for the UltraFit plug: (Regression line and prediction interval for each fitting procedure; intercept values are correct when single band attenuation equals to 0).

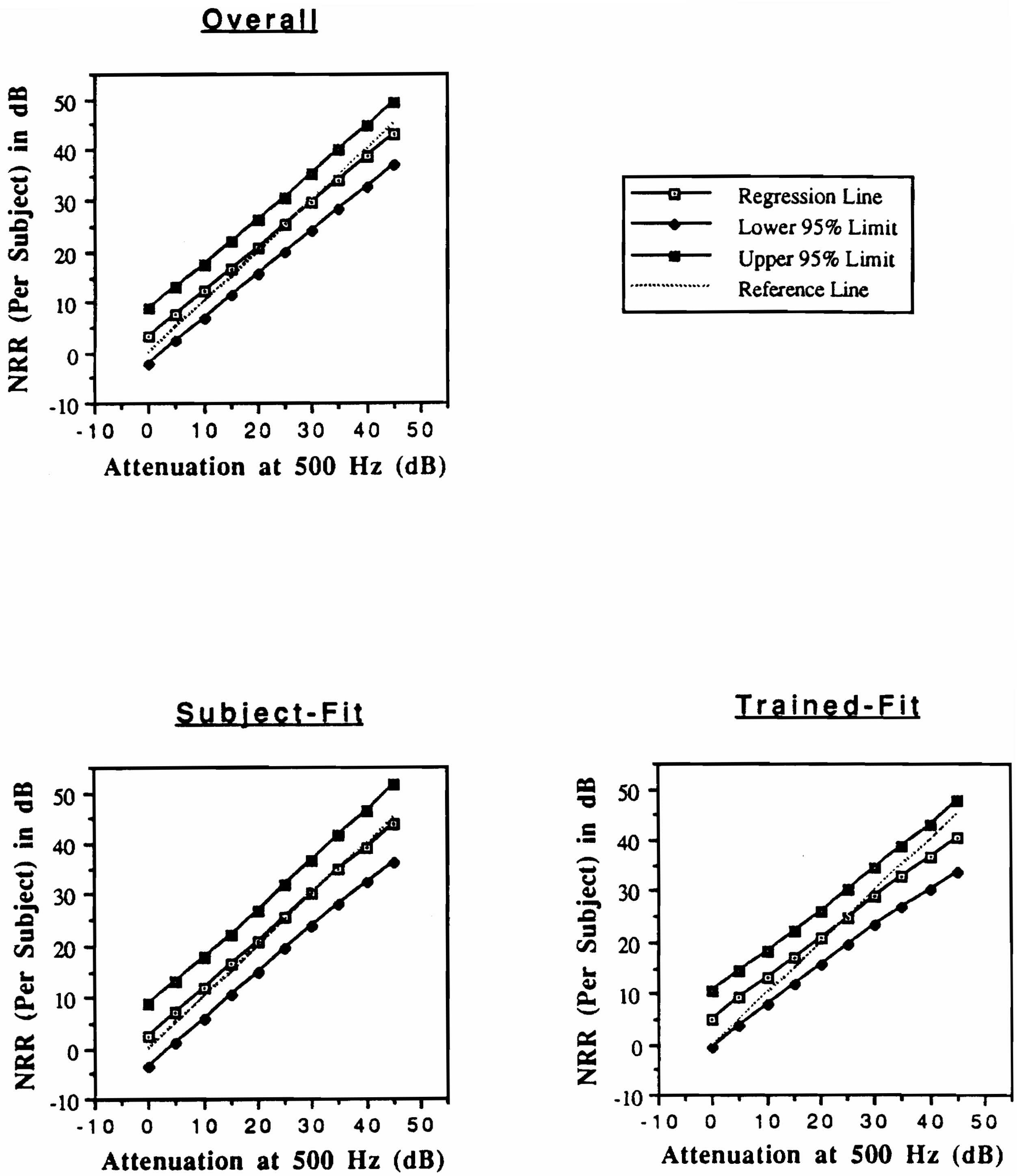


Figure 15. Prediction of field NRR$_{PS}$ from single 1/3-octave band (500 Hz) attenuation measurements for the Willson canal cap: (Regression line and prediction interval for each fitting procedure; intercept values are correct when single band attenuation equals to 0).

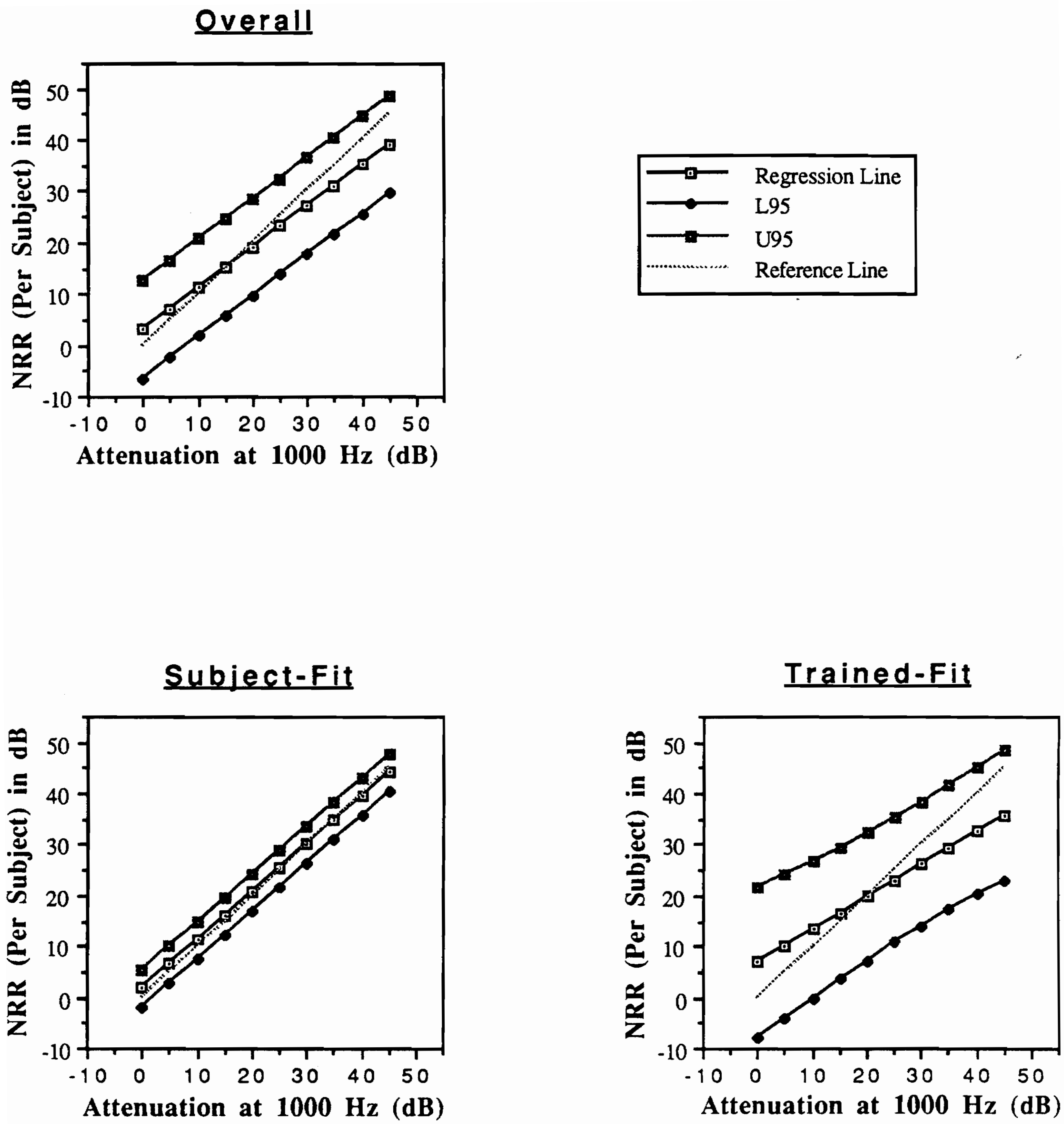


Figure 16. Prediction of field NRR_{PS} from single 1/3-octave band (1000 Hz) attenuation measurements for the E-A-R foam plug: (Regression line and prediction interval for each fitting procedure; intercept values are correct when single band attenuation equals to 0).

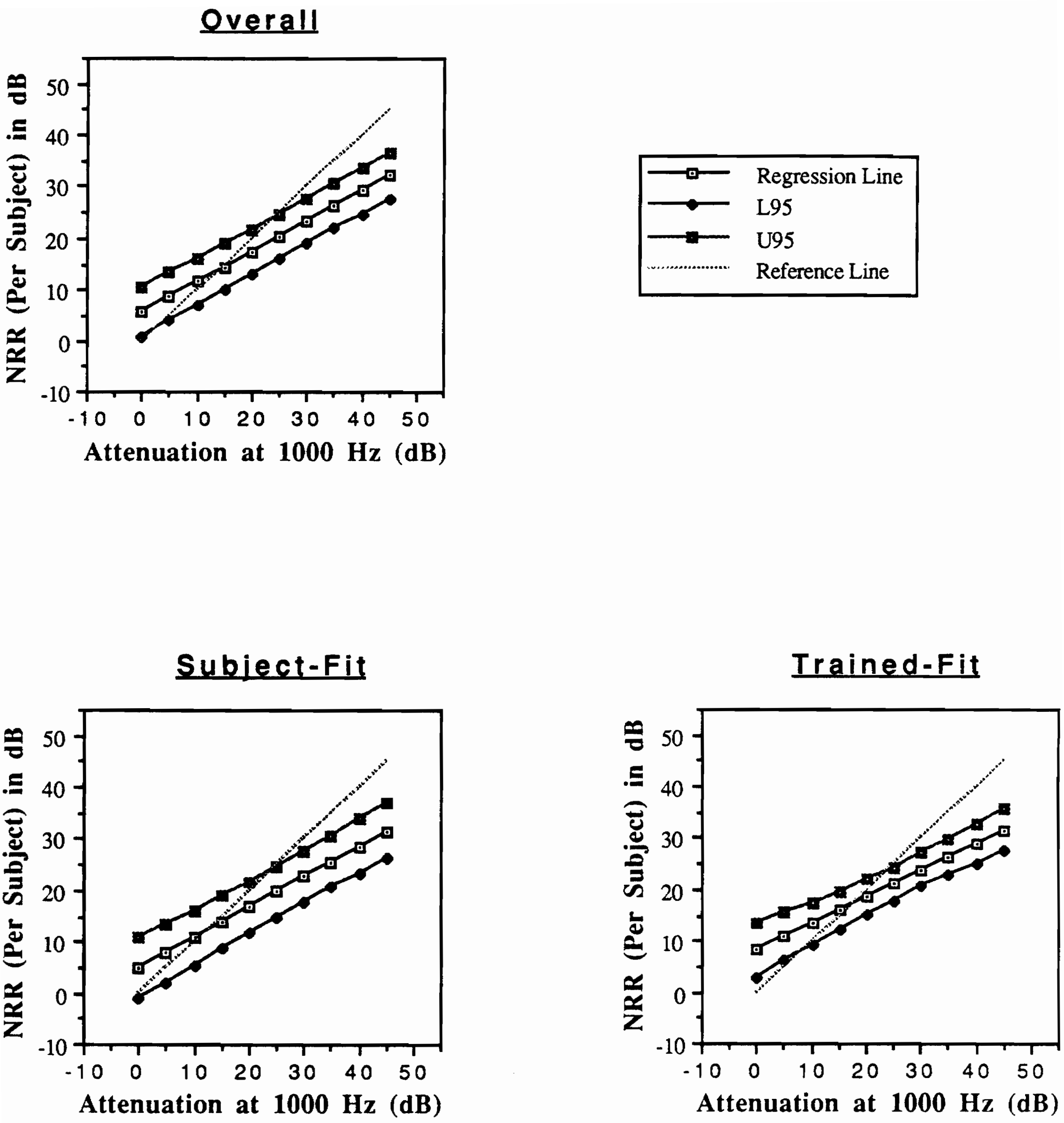


Figure 17. Prediction of field NRR$_{PS}$ from single 1/3-octave band (1000 Hz) attenuation measurements for the Bilsom UF-1 muff: (Regression line and prediction interval for each fitting procedure; intercept values are correct when single band attenuation equals to 0).

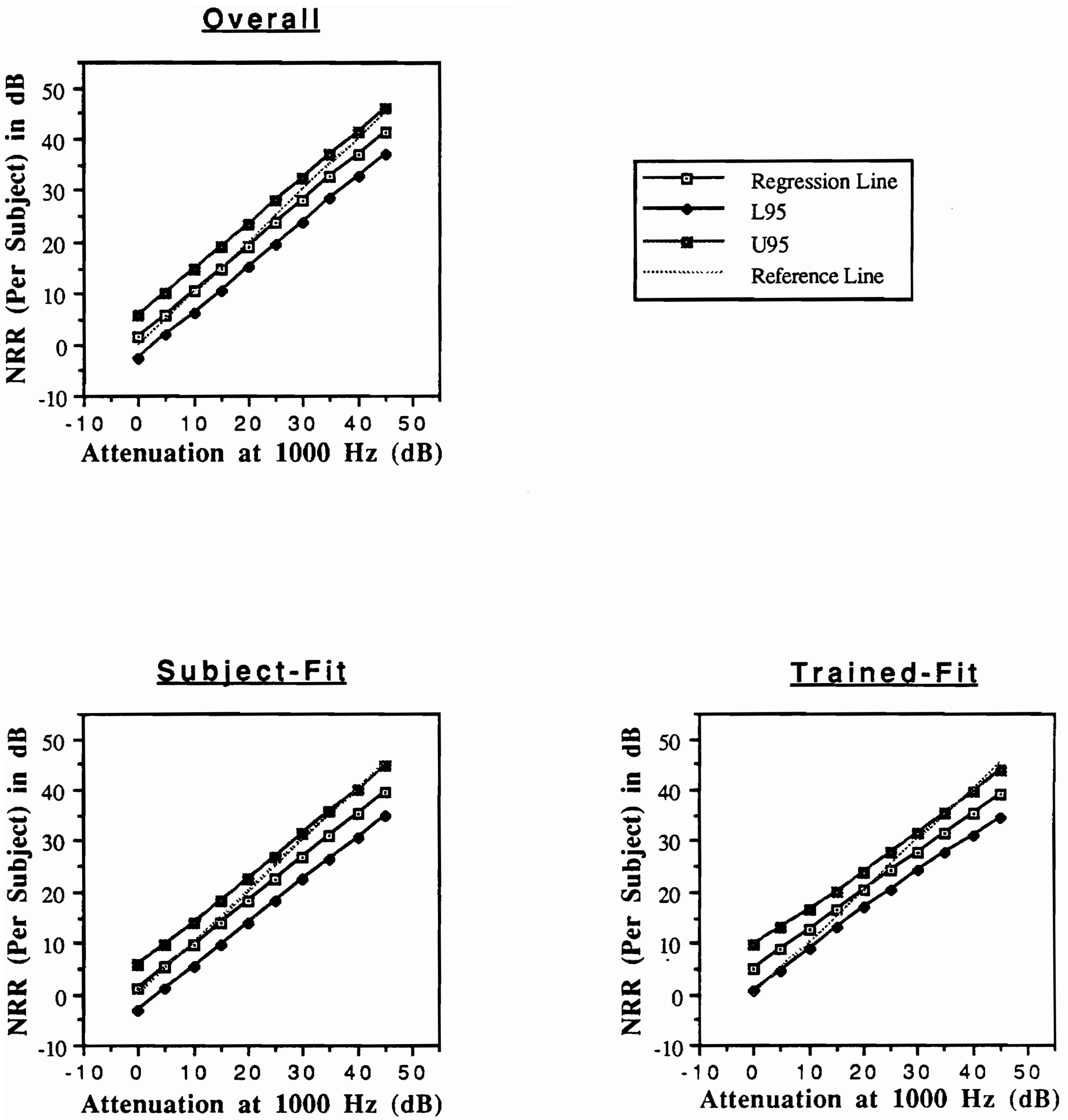


Figure 18. Prediction of field NRR$_{PS}$ from single 1/3-octave band (1000 Hz) attenuation measurements for the UltraFit plug: (Regression line and prediction interval for each fitting procedure; intercept values are correct when single band attenuation equals to 0).

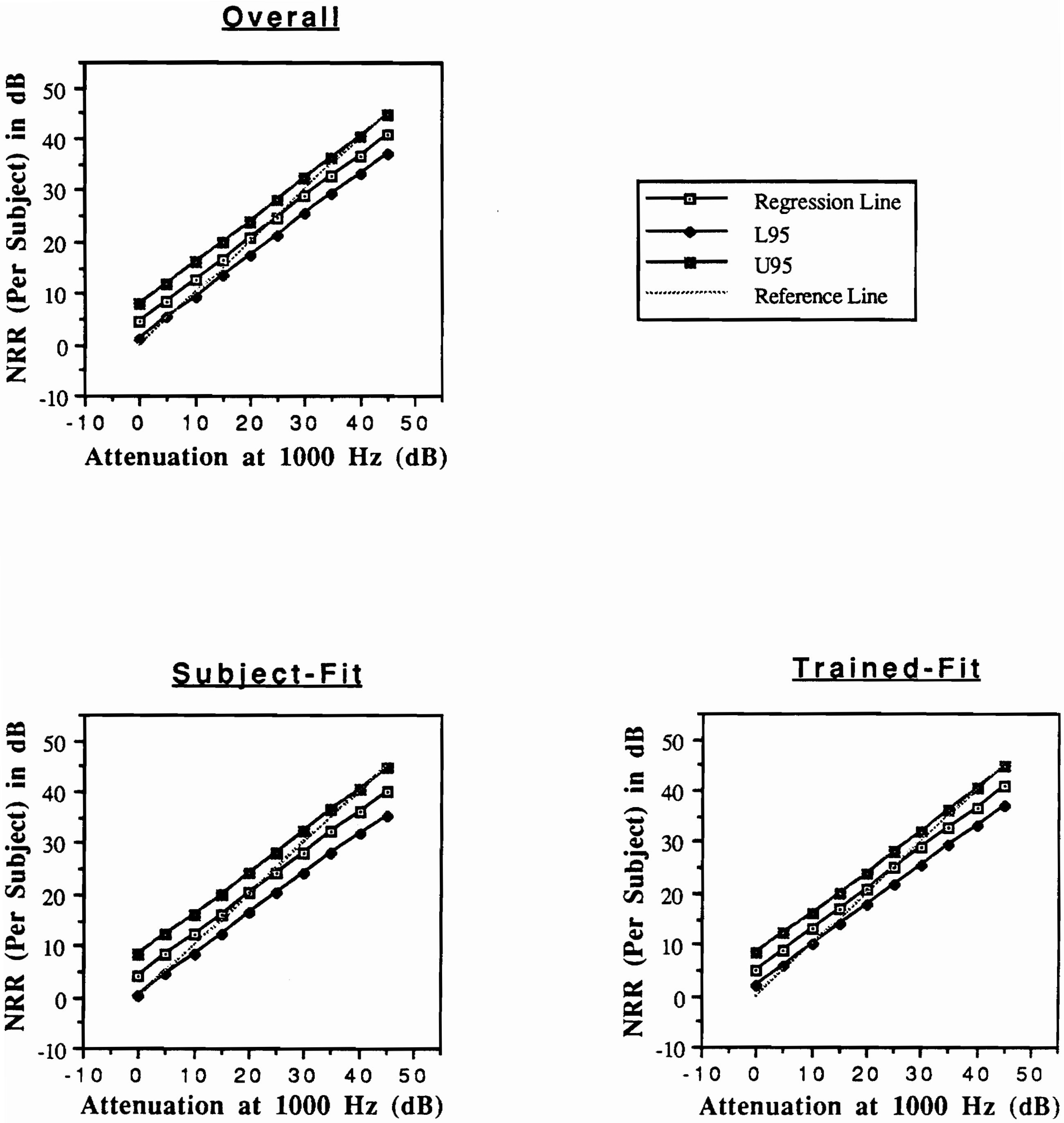


Figure 19. Prediction of field NRR_{PS} from single 1/3-octave band (1000 Hz) attenuation measurements for the Willson canal cap: (Regression line and prediction interval for each fitting procedure; intercept values are correct when single band attenuation equals to 0).

was a better predictor than AT1000, evidenced by slope values closer to 1 and higher correlation coefficient values. In addition, for AT500 and AT1000 values of 10 - 30 dB, which represent the attenuation range of primary interest in the field, the differences between the measured AT500/AT1000 values and the corresponding estimated NRR_{PS} values are presented in Tables 30 (AT500) and 31 (AT1000). Overall, the best prediction was accomplished for the UltraFit plug at both frequencies, evidenced by the smallest mean difference (0.9 dB across the AT500/AT1000 of 10 - 30 dB range) between the measured and the predicted attenuation (Tables 30 and 31), regression slopes closest to 1, intercepts closest to 0, and correlation coefficients closest to 1, as indicated in Tables 28 and 29.

When analyzed by each fitting procedure, all HPDs under the subject-fit condition provided approximately equal and excellent prediction performance for the AT500 analysis (Table 30): mean differences between predicted NRR_{PS} and actual 500 Hz attenuation data achieved by the four HPDs ranged only from 0.7 to 1.3 dB. The worst prediction of NRR_{PS} values in the AT500 analysis was achieved by the E-A-R foam plug under trained-fit, as indicated by the largest mean difference of 3.1 dB across the same AT500 range. Meanwhile, the AT1000 analysis (Table 31) demonstrated that the best and the worst predictions were performed by the E-A-R plug (mean difference of 1.1 dB) and the Bilsom muff (mean difference of 3.5 dB), respectively, both under the subject-fit condition. Again, all HPDs, except perhaps the Bilsom muff, provided good prediction performance under subject-fit, i.e., mean differences (for all HPDs except the muff) between the measured and the predicted attenuation ranged from 1.1 to 1.7 dB (Table 31). From Tables 30 and 31, it is noteworthy that the subject-fit condition provided prediction performance that was slightly, but consistently better than (or about equal to) the trained-fit condition. For both AT500 and AT1000 analyses, this prediction benefit under subject-fit was

Table 30. Differences Between the 500 Hz Attenuation Measurements and the Predicted NRR_{PS} Values (in dB) for Each HPD and Each Fitting Procedure

		Attenuation Measurement (in dB) at 500 Hz (AT500)					
		10	15	20	25	30	
HPD[1]	FIT						Average[2]
E	Overall	2.0	0.7	0.6	1.9	3.2	1.7
	Subject-Fit	1.6	1.2	0.8	0.4	0.1	0.8
	Trained-Fit	5.8	3.4	1.0	1.4	3.8	3.1
B	Overall	3.2	2.3	1.4	0.5	0.4	1.6
	Subject-Fit	2.7	2.0	1.2	0.5	0.2	1.3
	Trained-Fit	4.9	3.3	1.7	0.1	1.5	2.3
U	Overall	1.9	1.3	0.8	0.3	0.3	0.9
	Subject-Fit	1.3	0.8	0.3	0.2	0.7	0.7
	Trained-Fit	4.3	2.8	1.3	0.3	1.8	2.1
W	Overall	2.2	1.6	1.0	0.4	0.2	1.1
	Subject-Fit	1.7	1.3	1.0	0.6	0.2	1.0
	Trained-Fit	3.0	1.9	0.9	0.2	0.2	1.2

[1] E = E-A-R foam plug; B = Bilsom muff; U = UltraFit flanged plug; W = Willson canal cap.

[2] Averaged across the AT500 range of 10 - 30 dB.

Table 31. Differences Between the 1000 Hz Attenuation Measurements and the Predicted NRR_{PS} Values (in dB) for Each HPD and Each Fitting Procedure

		Attenuation Measurement (in dB) at 1000 Hz (AT1000)					
		10	15	20	25	30	
HPD[1]	FIT						Average[2]
E	Overall	1.2	0.2	0.8	1.8	2.8	1.4
	Subject-Fit	1.2	0.9	0.6	0.3	0.0	1.1
	Trained-Fit	3.4	1.6	0.2	2.0	3.7	2.2
B	Overall	1.6	0.4	2.5	4.6	6.7	3.2
	Subject-Fit	0.8	1.2	3.2	5.2	7.3	3.5
	Trained-Fit	3.4	1.0	1.4	3.8	6.2	3.2
U	Overall	0.4	0.1	0.7	1.3	1.9	0.9
	Subject-Fit	0.2	1.0	1.7	2.4	3.2	1.7
	Trained-Fit	2.6	1.4	0.2	1.0	2.2	1.5
W	Overall	2.6	1.6	0.7	0.3	1.3	1.3
	Subject-Fit	2.3	1.3	0.2	0.8	1.8	1.3
	Trained-Fit	3.0	1.9	0.9	0.1	1.1	1.4

[1] E = E-A-R foam plug; B = Bilsom muff; U = UltraFit flanged plug; W = Willson canal cap.

[2] Averaged across the AT1000 range of 10 - 30 dB.

particularly pronounced for the E-A-R foam plug. Although an explanation of this discrepancy of the foam plug in prediction performance between the two fitting procedures is not readily obvious, the difference is practically very useful in that the subject-fit condition, which mimicked most actual field fitting conditions, performed better in predicting field NRR_{PS} values than the trained-fit condition, which would only occur in the best hearing conservation programs. Since all HPDs under subject-fit yielded reasonable to excellent prediction results, reliable prediction of NRR_{PS} from the single-frequency (500 Hz or 1000 Hz) field attenuation data (i.e., obtained without any training) is very feasible and practical.

Prediction intervals

To estimate certain probabilistic bounds within which particular NRR_{PS} values fall, with a given certainty (say, 95%), for single-frequency attenuation measurements, prediction intervals (Myers, 1986) were constructed. The prediction interval (PI) is a probability bound within which a particular (i.e., single) observation $\hat{y}$ is expected to fall with a certain probability for the given predictor value x_0. A PI differs from a typical confidence interval (CI) in that a CI reflects bounds within which the mean $\hat{y}_0$ is expected to fall with a fixed probability for the given x_0. In other words, PIs represent intervals constructed for bounding single (not mean) observations. The prediction interval (PI) on a single response observation y_0, with a fixed probability (1 - α), at $x = x_0$ is given by Myers (1986, p 36) as

$$\hat{y}(x_0) \pm [t_{(\alpha/2,\ n-2)}]s\sqrt{1 + \frac{1}{n} + \frac{(x_0 - \bar{x})^2}{S_{xx}}}\ ,$$

$$\text{where } S_{xx} = \sum_{i=1}^{n}(x_i - \bar{x})^2,$$

$$s = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-2}}\text{, and}$$

$$\hat{y} = b_0 + b_1 x \sim \text{least square regression line}$$

$$\text{with a slope } b_1 \text{ and an intercept } b_0$$

For the purpose of this study, the PI approach was used to predict a particular NRR_{PS} value with 95% probability (i.e., 95% PI) from the given 500 Hz and 1000 Hz attenuation measurements (i.e., AT500 and A1000, respectively). Using the 95% PIs, an individual's minimum (or maximum) attainable field NRR_{PS} value can be estimated, with a 95% probability, from a 500 or 1000 Hz attenuation measurement. For example, from the subject-fit results of the E-A-R foam plug shown in Figure 12, a minimum NRR_{PS} of 20 dB is expected with 95% certainty from a measured 500 Hz attenuation of 25 dB. For each HPD and each fitting procedure, the PIs (denoted as L95 and U95 for Lower and Upper 95% Limit, respectively) constructed over the AT500/AT1000 range of 0 - 45 dB are illustrated in Figures 12 through 15 (for the AT500 results) and Figures 16 through 19 (for the AT1000 results), respectively. In addition, calculated PIs at AT500 (and AT1000) of 10, 20, and 30 dB (i.e., spanning the practical predictor range for field application) are also presented in Tables 32 and 33, respectively.

From Figures 12 through 19 and Tables 32 and 33, it can be seen that magnitudes of the PIs are quite different among the different types of HPDs and moderately different across the two fitting conditions, although the widths of the PIs are generally constant (in the 10 - 30 dB range of AT500 and AT1000) for all regression lines with few exceptions (e.g., trained-fit data for the Bilsom muff). When the 500 Hz data were collapsed across the two fitting conditions (i.e., overall data), the

Table 32. 95% Prediction Intervals on NRR_{PS} (in dB) for Each HPD and Each Fitting Procedure (Using 500 Hz Attenuation Data)

		Attenuation Measurement (in dB) at 500 Hz (AT500)		
		10	20	30
HPD[1]	FIT			
E	Overall	± 10.3	± 10.2	± 10.2
	Subject-Fit	± 4.9	± 4.9	± 4.9
	Trained-Fit	± 13.4	± 12.7	± 12.4
B	Overall	± 3.1	± 3.0	± 3.1
	Subject-Fit	± 2.8	± 2.7	± 2.9
	Trained-Fit	± 4.1	± 3.3	± 3.9
U	Overall	± 4.4	± 4.4	± 4.5
	Subject-Fit	± 5.1	± 5.2	± 5.4
	Trained-Fit	± 3.1	± 3.0	± 3.1
W	Overall	± 5.3	± 5.3	± 5.6
	Subject-Fit	± 5.9	± 6.0	± 6.5
	Trained-Fit	± 5.1	± 5.1	± 5.5

[1] E = E-A-R foam plug; B = Bilsom muff; U = UltraFit flanged plug; W = Willson canal cap.

Table 33. 95% Prediction Intervals on NRR_{PS} (in dB) for Each HPD and Each Fitting Procedure (Using 1000 Hz Attenuation Data)

		Attenuation Measurement (in dB) at 1000 Hz (AT1000)		
		10	20	30
HPD[1]	FIT			
E	Overall	± 9.4	± 9.4	± 9.4
	Subject-Fit	± 3.6	± 3.5	± 3.6
	Trained-Fit	± 13.6	± 12.6	± 12.2
B	Overall	± 4.5	± 4.2	± 4.2
	Subject-Fit	± 5.4	± 5.0	± 4.9
	Trained-Fit	± 4.2	± 3.4	± 3.2
U	Overall	± 4.2	± 4.2	± 4.2
	Subject-Fit	± 4.3	± 4.3	± 4.5
	Trained-Fit	± 3.8	± 3.5	± 3.7
W	Overall	± 3.3	± 3.4	± 3.5
	Subject-Fit	± 3.8	± 3.9	± 4.1
	Trained-Fit	± 3.0	± 3.0	± 3.2

[1] E = E-A-R foam plug; B = Bilsom muff; U = UltraFit flanged plug; W = Willson canal cap.

narrowest (an average of ± 3.1 dB across the 10 - 30 dB AT500 range) and the widest (an average of ± 10.2 dB across the same AT500 range) PIs were obtained for the Bilsom muff and the E-A-R plug, respectively (Table 32). Across the same attenuation range of 10 - 30 dB for the AT1000 analysis, the Willson canal cap and the E-A-R plug provided the narrowest (an average of 3.4 dB) and the widest (an average of 9.4 dB) PIs, as indicated in Table 33. When considering the separate data for each fitting procedure in the AT500 of 10 - 30, the width of the PI was narrowest (an average of ± 2.8 dB) for the Bilsom muff under subject-fit and widest (an average of ± 12.8 dB) for the E-A-R plug under the trained-fit condition (Table 32). On the other hand, the AT1000 results (Table 33) showed the narrowest (an average of ± 3.1 dB) and the widest (an average of ± 12.8 dB) PIs, respectively for the Willson canal cap under trained-fit and the E-A-R plug under the trained-fit condition.

The major point which distills from the above analysis is that, in general, the subject-fit data in the AT500 analysis provided PIs narrower (i.e., better prediction) than, or nearly equal to, those achieved with the trained-fit data (with one exception for the UltraFit plug). The advantage of the subject-fit data was pronounced for the E-A-R plug for both AT500 and AT1000 analyses, though the AT1000 subject-fit data provided slightly wider PIs for other HPDs than did the AT1000 trained-fit results. Although an explanation of this slight discrepancy in prediction performance between the two fitting procedures (as evidenced in Tables 32 and 33 and Figures 12 through 19) is not readily apparent, using the subject-fit single-frequency (preferably 500 Hz, based primarily on the slightly better prediction performance benefit found in this study) data for predicting field NRR_{PS} is again considered practically very useful in field applications, as discussed previously.

RESULTS: COMFORT DATA

Comfort analyses were performed on 2 sets of data : (1) comfort index data, which were amenable to parametric statistical procedures, and (2) convenience rating (overall experience) data, which were scrutinized using graphical plots.

Comfort Index Data Analysis

The objectives of the comfort index analysis were to (1) determine which of the 14 bipolar scales accurately represented the subject's perception of HPD comfort and thereby develop a single-number "global" comfort measure from the composite of individual scales, i.e., the "comfort index" (hereafter CI), and (2) investigate the effects of different levels of HPD fitting procedure and time of use variables on this CI for each HPD.

CI Data Reduction

Subject responses to 7-step bipolar comfort rating scales (Appendix M) were converted to a numerical value, ranging from 1 to 7 in left-to-right fashion. For each scale, the response interval most closely associated with the left-end descriptor in the bipolar pair was coded as 1; the response interval most closely related to the right-end adjective was coded as 7. The correlation of each coded scale with the "Uncomfortable - Comfortable" scale was next determined. Because comfort was the hypothetical construct of major interest, any scale achieving a high correlation with the "Uncomfortable - Comfortable" scale would likely be eliciting certain feelings influencing the subject's perception of global HPD comfort (Casali et al., 1987). The correlation results using the Spearman correlation coefficient (r_s) are presented in the column labeled "Field Study" in Table 34.

The scales which met the a priori cutoff criteria (statistically significant at $p < 0.05$ and $|r_s| > 0.45$) were used to develop the comfort index (CI) along with the "Uncomfortable - Comfortable" scale. The rationale for this cutoff strategy was that any scale item having a small correlation with the "Uncomfortable - Comfortable" scale could be treated as practically (though not statistically) nonsignificant and thus should be deleted (Chatfield and Collins, 1980) from inclusion in the CI calculation. Six scales, including the "Uncomfortable - Comfortable" scale, were incorporated into the field study CI calculation, as shown in the column labeled "Field Study" in Table 34. In comparison, for the laboratory comfort data (Park and Casali, 1990), 7 scales (including the "Uncomfortable - Comfortable" scale) made up the CI using the same cutoff criteria (see the "Laboratory Study" column in Table 34). There was good agreement between the rating scale correlation results for the laboratory and field experiments; only the "Soft - Hard" scale was not common to the CI computation for both studies, as it did not exceed the $|r_s| > 0.45$ cutoff in the field results. Prior to computing the CI, it was necessary that each scale value be adjusted on the basis of the sign (direction) of the r_s. That is, for those scales with negative r_s values, the direction of the numerical values was reversed (e.g., 7 to 1, 6 to 2, 5 to 3, and vice versa) to keep a consistent directional relationship with the uncomfortable-comfortable scale. Then, the CI was computed as the linear sum of these 7 scales' equally weighted numerical values. The resultant CI values ranged from 7 (most uncomfortable) to 49 (most comfortable), i.e., in a 43-point scale; these were treated as the dependent measure for subsequent data analysis.

Table 34. Spearman Correlation Coefficient (r_S) for Each Bipolar Comfort Rating Scale with the Uncomfortable-Comfortable Scale (Laboratory and Field Data)

	Laboratory Study		Field Study	
Bipolar Scale*	r_s	p	r_s	p
Painless - Painful	-0.62**	< 0.05	-0.55**	< 0.05
No Uncomfortable Pressure - Uncomfortable Pressure	-0.73**	< 0.05	-0.73**	< 0.05
Intolerable - Tolerable	0.55**	< 0.05	0.48**	< 0.05
Tight - Loose	0.27	< 0.05	0.22	< 0.05
Not Bothersome - Bothersome	-0.73**	< 0.05	-0.73**	< 0.05
Heavy - Light	0.43	< 0.05	0.19	< 0.05
Cumbersome - Not Cumbersome	0.46**	< 0.05	0.46**	< 0.05
Soft - Hard	-0.52**	< 0.05	-0.37	< 0.05
Cold - Hot	-0.23	< 0.05	-0.01	> 0.05
Smooth - Rough	-0.37	< 0.05	-0.29	< 0.05
Feeling of Complete Isolation - No Feeling of Complete Isolation	0.03	> 0.05	0.21	< 0.05
Ear Open - Ear Blocked	-0.22	< 0.05	-0.31	< 0.05
Ear Empty - Ear Full	-0.31	< 0.05	-0.38	< 0.05

* In each scale, the response interval most closely related to the left descriptive adjective in the bipolar pair was coded as a 1, and the response interval most closely related to the right descriptive adjective was coded as a 7.

** Indicates scales incorporated into the Comfort Index using cutoff criteria of $|r_s| > 0.45$ and $p < 0.05$

CI Statistical Analysis

A 3-way, mixed-factors ANOVA (with the same sources of variance used in the previous attenuation data analysis) was applied to the field CI data, and the results of the ANOVA are summarized in Table 35. Statistically significant ($p < 0.05$) effects included fitting procedure-by-time of use-by-HPD (F x T x H), fitting procedure-by-HPD (F x H), and a main effect of HPD type (H). For these significant ANOVA effects, the same post-hoc analysis procedures as used for the attenuation data analyses were applied to determine the loci of significance. A brief discussion of significant effects follows.

Fitting procedure-by-time of use-by-HPD interaction: The significant 3-way interaction was further broken down using simple interaction effect *F*-tests to analyze the F x T interaction effect for each HPD. According to the results (Table 36), out of the 4 HPDs evaluated, only the E-A-R foam plug exhibited significance, whereas no changes were found with other HPDs. That is, user comfort provided by the foam plug changed under different fitting procedures over the 3-week HPD use. For the foam plug, further simple effect *F*-tests (Table 36) were applied to examine comfort changes over time under each fitting procedure, followed by Bonferroni *t*-tests for pairwise comparisons (Table 37). Under subject-fit, improved comfort occurred after 2 weeks of HPD usage, but no significant ($p < 0.05$) comfort difference was observed between the first and third week due to a comfort decrease in the third week back to the initial level. On the other hand, no significant comfort change over the 3-week period was found under trained-fit.

Fitting procedure-by-HPD interaction: Device-specific fitting procedure effects were revealed by this interaction. The simple effect *F*-tests (Table 36) indicated that the

Table 35. ANOVA Summary Table for Comfort Analysis Using the Field Comfort Index Data

Source	*df*	*SS*	*F*	*p*
Between-Subjects				
HPD Type (H)	3	5461.61	9.79	0.0001
Subjects (S/H)	36	6697.22		
Within-Subjects				
Fitting Procedure (F)	1	182.00	3.24	0.0801
F x H	3	506.57	3.01	0.0431
F x S/H	36	2019.55		
Time of Use (T)	2	31.41	1.30	0.2778
T x H	6	53.13	0.74	0.6229
T x S/H	72	867.13		
F x T	2	28.96	1.71	0.1877
F x T x H	6	131.91	2.60	0.0245
F x T x S/H	72	608.80		
Total	239	16588.29		

Table 36. Results of Simple Effect *F*-Tests[1] for the Significant Interaction Effects Post-hoc Analysis (Comfort Index Data)

	HPD[2]	U	E	B	W
<u>F x T x H Interaction [Step 1]</u>					
	MS_{FxT}	21.07	30.15	26.14	1.40
	$MS_{FxTxS(H)}$	8.46	8.46	8.46	8.46
	F[3]	2.49	3.57	3.09	0.16
	p	>0.05	<0.05	>0.05	>0.05
<u>F x T x H Interaction [Step 2]</u>					
Subject-Fit	MS_T	17.04	35.23	19.60	21.74
	$MS_{FxTxS(H)}$	8.46	8.46	8.46	8.46
	F[4]	2.01	4.16	2.31	2.57
	p	>0.05	<0.01	>0.05	>0.05
Trained-Fit	MS_T	6.10	3.43	9.44	10.14
	$MS_{FxTxS(H)}$	8.46	8.46	8.46	8.46
	F[4]	0.72	0.41	1.12	1.20
	p	>0.05	>0.05	>0.05	>0.05
<u>F x H Interaction</u>					
	MS_F	3.27	470.40	28.20	153.60
	$MS_{FxS(H)}$	56.10	56.10	56.10	56.10
	F[5]	0.06	8.39	0.50	2.73
	p	>0.05	<0.05	>0.05	>0.05

---

[1] To determine the difference in fitting procedure-by-time of use interaction for each HPD (Step 1 of F x T x H post-hoc); To determine the difference in time of use effects for each fitting procedure and each HPD (Step 2 of F x T x H post-hoc);

To determine the difference in fitting procedure effect for each HPD (F x H post-hoc).

[2] U = UltraFit flanged plug; E = E-A-R foam plug; B = Bilsom muff; W = Willson canal cap.

[3] $F = \frac{MS_{FxT}(df=2)}{MS_{FxTxS(H)}(df=72)}$; $F_{(.05,2,72)} = 3.13$; $F_{(.01,2,72)} = 4.94$

[4] $F = \frac{MS_{T}(df=2)}{MS_{FxTxS(H)}(df=72)}$; $F_{(.05,2,72)} = 3.13$; $F_{(.01,2,72)} = 4.94$

[5] $F = \frac{MS_{F}(df=1)}{MS_{FxS(H)}(df=36)}$; $F_{(.05,1,36)} = 4.12$; $F_{(.01,1,36)} = 7.41$

Table 37. Results of Bonferroni *t*-Test[1] for the Fitting Procedure-by-Time of Use-by-HPD (F x T x H) Interaction Post-hoc Analysis (Comfort Index Data[2])

HPD[3]		U	E	B	W
CD[4]			3.2		
Fitting Condition	Time[5]				
Subject-Fit	W1	29.6 A	30.6 B	25.8 A	17.6 A
	W2	27.0 A	34.3 A	28.6 A	19.8 A
	W3	28.1 A	31.9 A B	27.2 A	20.4 A
Trained-Fit	W1	27.8 A	27.1 A	29.4 A	15.0 A
	W2	29.2 A	26.0 A	27.5 A	16.2 A
	W3	29.1 A	26.9 A	28.8 A	17.0 A

[1] Only these results for the E-A-R foam plug were analyzed using Bonferroni *t*-test, because other HPDs were not found to be sensitive to time of use effects in simple effect *F*-tests from Table 36 (mean data presented for only comparison purposes).

[2] Means (n = 10) within a table column with the different letter are significantly different at $p < 0.05$, according to Bonferroni *t*-test which followed simple effect *F*-tests from Table 36.

Means (n = 10) within a table column with the same letter are not significantly different at $p < 0.05$, according to the results of simple effect *F*-tests from Table 36.

Higher comfort index values indicate more comfort on a composite scale from 7 to 49.

[3] U = UltraFit flanged plug; E = E-A-R foam plug; B = Bilsom muff; W = Willson canal cap.

[4] Critical Difference $(CD) = t'_{\alpha}(c, df_{Error})\sqrt{\frac{2MS_{FxTxS(H)}}{n}}$

where $c = 3$, $df_{Error} = 72$, $n = 10$, $\alpha = 0.05$, and $t'_{0.05}(3, 72) = 2.46$

[5] W1 = Week 1; W2 = Week 2; W3 = Week 3.

E-A-R foam plug was the only HPD that differed between the two fitting conditions. Further means comparisons (Table 38 and Figure 20) demonstrated that the E-A-R plug was perceived as more comfortable (by 6 CI points) in the subject-fit condition than in the trained-fit condition. On the other hand, the UltraFit plug and the Bilsom muff showed a very slight, though statistically nonsignificant, trend toward increased comfort due to training.

HPD main effect: A highly significant ($p < 0.01$) comfort difference was found among the 4 HPDs used in the field study when the data were collapsed across fitting procedure and time of use. This result was somewhat anticipated on the basis of previous reports (e.g., Behar and Desormeaux, 1986; Sweetland, 1981) that various HPDs differ noticeably in user-rated comfort in the field. The results of Newman-Keuls tests (Table 39 and Figure 21) showed that the comfort achieved over the 6-week usage period with 3 of the 4 HPDs evaluated (E-A-R plug, UltraFit plug, and Bilsom muff) was essentially not different across devices. However, the canal cap was rated significantly ($p < 0.05$) more uncomfortable than the other 3 devices tested. The mean CI difference between the E-A-R plug and the canal cap was approximately 12 points. The reported long-term discomfort for the canal cap device was expected because workers expressed complaints of pain due to localized pressure, especially in the conchal and tragal areas of the outer ear. This result demonstrates that the canal cap is best suited for intermittent use, as most of the workers tested wore their HPDs continuously on the job.

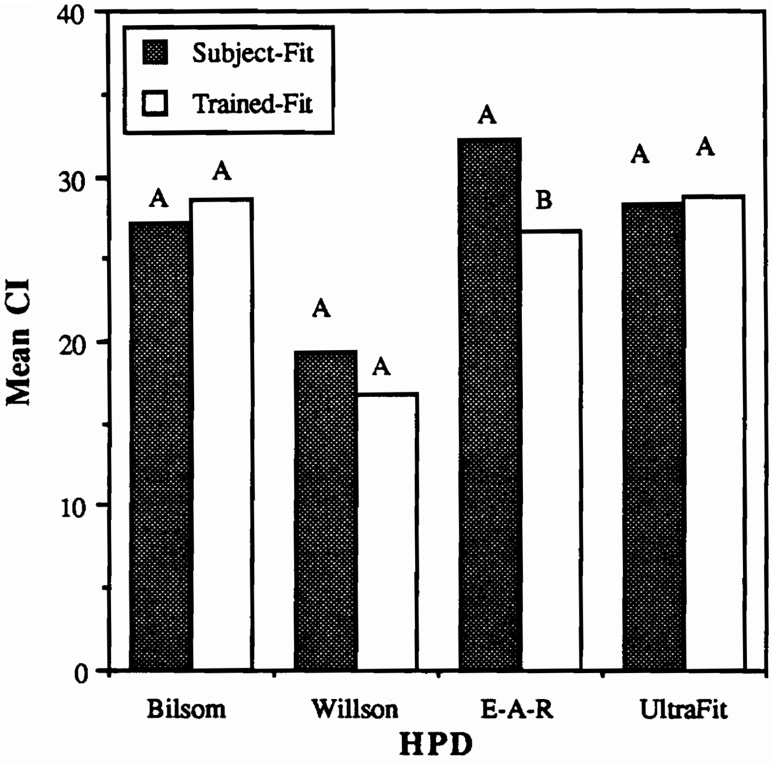
Table 38. Means[1] Comparisons for the Fitting Procedure-by-HPD (F x H) Interaction Effects Post-hoc Analysis (Comfort Index Data[2])

HPD[3]	U	E	B	W
Fit Condition	Mean CI	Mean CI	Mean CI	Mean CI
Subject-Fit	28.23 A	32.27 A	27.20 A	19.27 A
Trained-Fit	28.70 A	26.67 B	28.56 A	16.70 A

[1] Means (n = 30) with different letters are significantly different at $p < 0.05$, according to the results of simple effect *F*-test from Table 36.

[2] Higher comfort index values indicate more comfort on a composite scale from 7 to 49.

[3] U = UltraFit flanged plug; E = E-A-R foam plug; B = Bilsom muff; W = Willson canal cap.



Higher CI values indicate more comfort; HPDs described in text.

Figure 20. **Field comfort index data for each HPD under each fitting procedure:** (Means with different letters for each HPD are significantly different at $p < 0.05$).

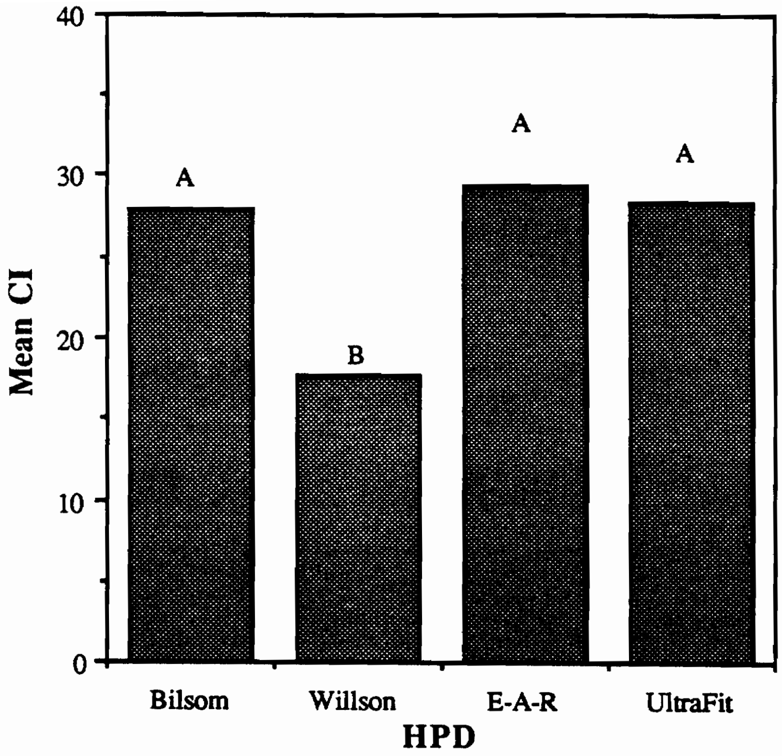
Table 39. Results of Newman-Keuls Test for the HPD Main Effect Post-hoc Analysis (Comfort Index Data[1])

HPD[2]	Mean[3] CI
E	29.47 A
U	28.47 A
B	27.88 A
W	17.67 B

[1] Higher comfort index values indicate more comfort on a composite scale from 7 to 49.

[2] E = E-A-R foam plug; U = UltraFit flanged plug; B = Bilsom muff; W = Willson canal cap.

[3] Means (n = 60) within a table column with the different letter are significantly different at $p < 0.05$, according to the ANOVA results from Table 35.



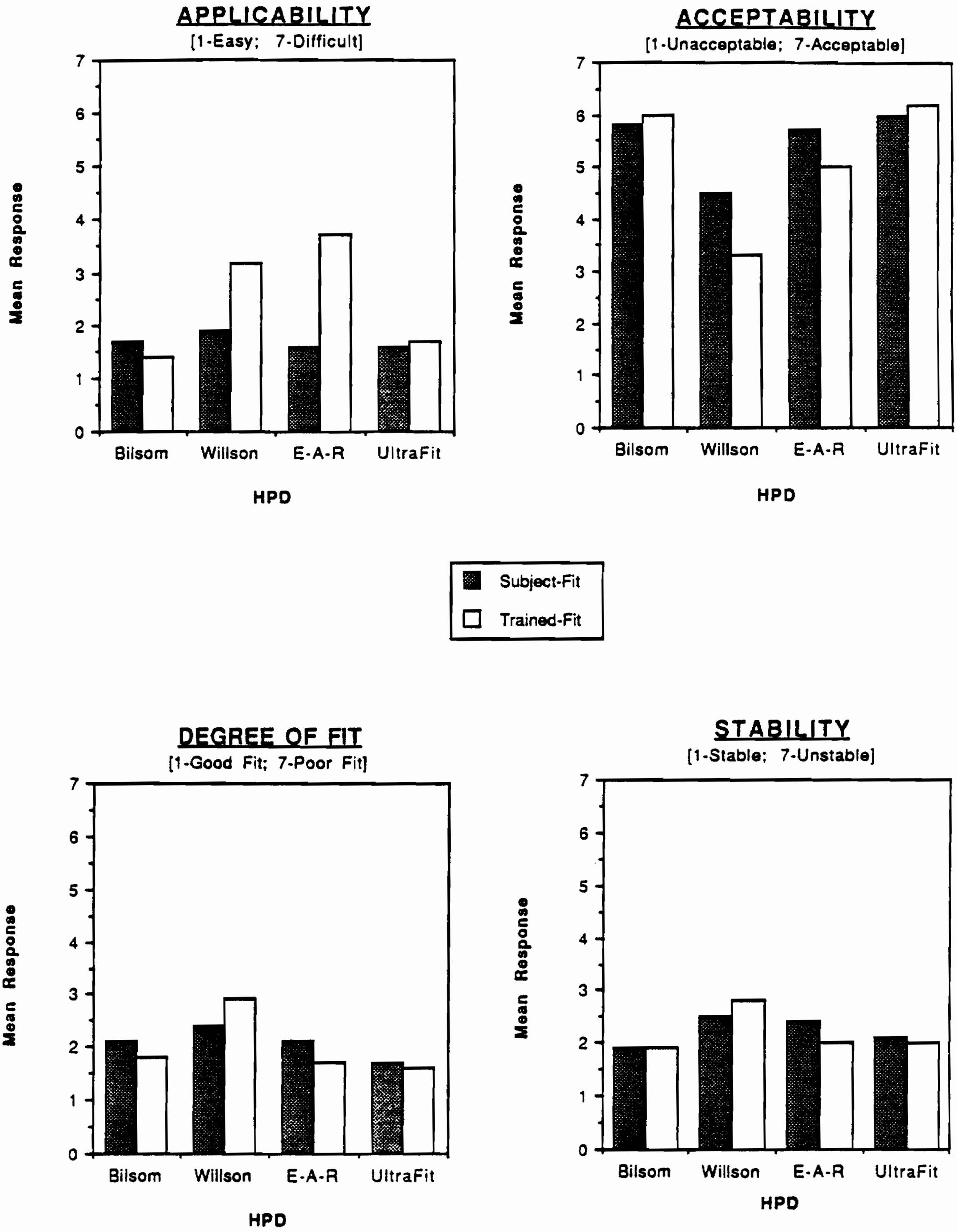
Higher CI values indicate more comfort; HPDs described in text.

Figure 21. Field comfort index data for each HPD: (Means with different letters are significantly different at $p < 0.05$).

Convenience Data Analysis

The objective of the convenience data analysis was to ascertain the subjects' experience-based perceptions after using the HPDs over a long use period of 3 weeks under each fitting condition. These perceptions were based on 8 different qualities measured using the 8 bipolar convenience rating scales. Unlike the comfort rating scales, there was no major hypothetical construct of interest for the experience perceptions data; therefore, analyses were accomplished without converting the data into any single-number index. Instead, the 8 different sets of convenience data were graphed and reviewed individually. Since each scale's data showed a clustered distribution, suggesting that a violation of the normality assumption occurred, parametric statistical procedures were not justified. Thus, interpretation was based on descriptive plots of subject responses on the individual convenience rating scales.

Subject responses (i.e., overall experience) to the 8 convenience rating scales (Appendix N) were first coded for each scale as numerical values of 1 to 7 in left-to-right fashion. Then, mean response values for each scale dimension were plotted for each fitting procedure and each HPD, as illustrated in Figure 22. *The discussion of convenience differences which follow is based only on a visual interpretation of the data and does not imply statistical or practical significance.* Of the 4 HPDs investigated, the Willson canal cap was judged as the least acceptable and attractive HPD and also as providing the poorest fit in the field. On the other hand, it was rated as the simplest device to use. Workers judged the premolded UltraFit plug and the Bilsom muff as the most acceptable devices and rated both as easy to apply. Although the E-A-R foam plug was approximately equal in acceptability and attractiveness to the UltraFit plug and the Bilsom muff under the subject-fit condition, the workers considered the foam plug the most complex HPD to use when they were



APPLICABILITY [1-Easy; 7-Difficult]

ACCEPTABILITY [1-Unacceptable; 7-Acceptable]

DEGREE OF FIT [1-Good Fit; 7-Poor Fit]

STABILITY [1-Stable; 7-Unstable]

Figure 22. Field data mean response plots of fitting procedure for each HPD (described in text) on each convenience rating scale.

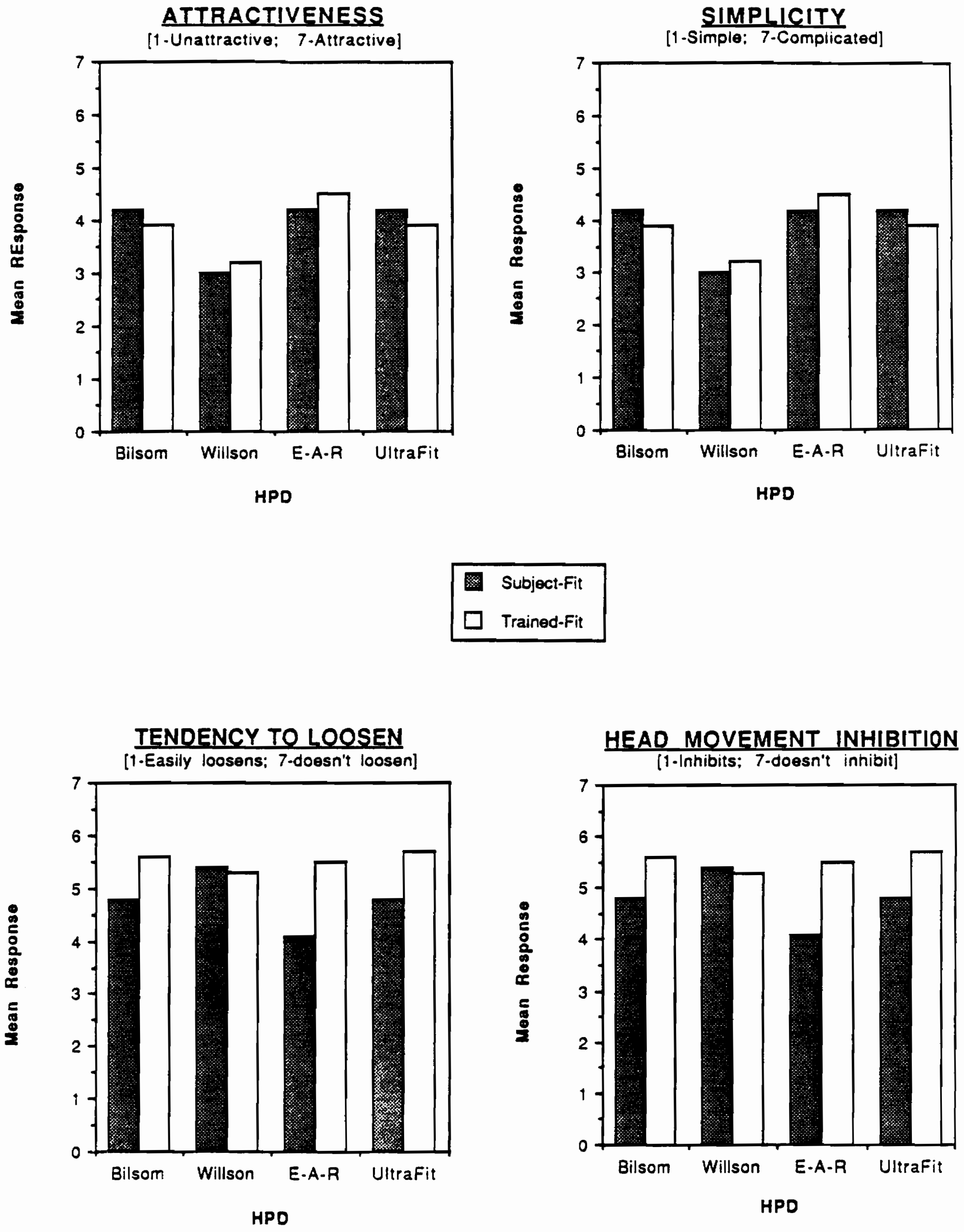


Figure 22. Field data mean response plots of fitting procedure for each HPD (described in text) on each convenience scale (Continued).

provided with the proper training in device fit. The Bilsom muff was rated as slightly more stable than the other HPDs in the field condition. Finally, noticeable fitting procedure influences for the E-A-R foam plug were observed in the "Applicability," the "Tendency to Loosen," and the "Head Movement Inhibition" scales.

RESULTS: CONTRAST OF LABORATORY AND FIELD DATA

A major objective of this field study was to yield attenuation and comfort data which were obtained with similar HPDs, fitting, and test environment (REAT) conditions to those of the precursor laboratory study, and thus enable direct field versus laboratory comparisons on a common basis. A central issue was how well the laboratory work activity protocol could simulate the influence of actual workplace conditions on HPD performance.

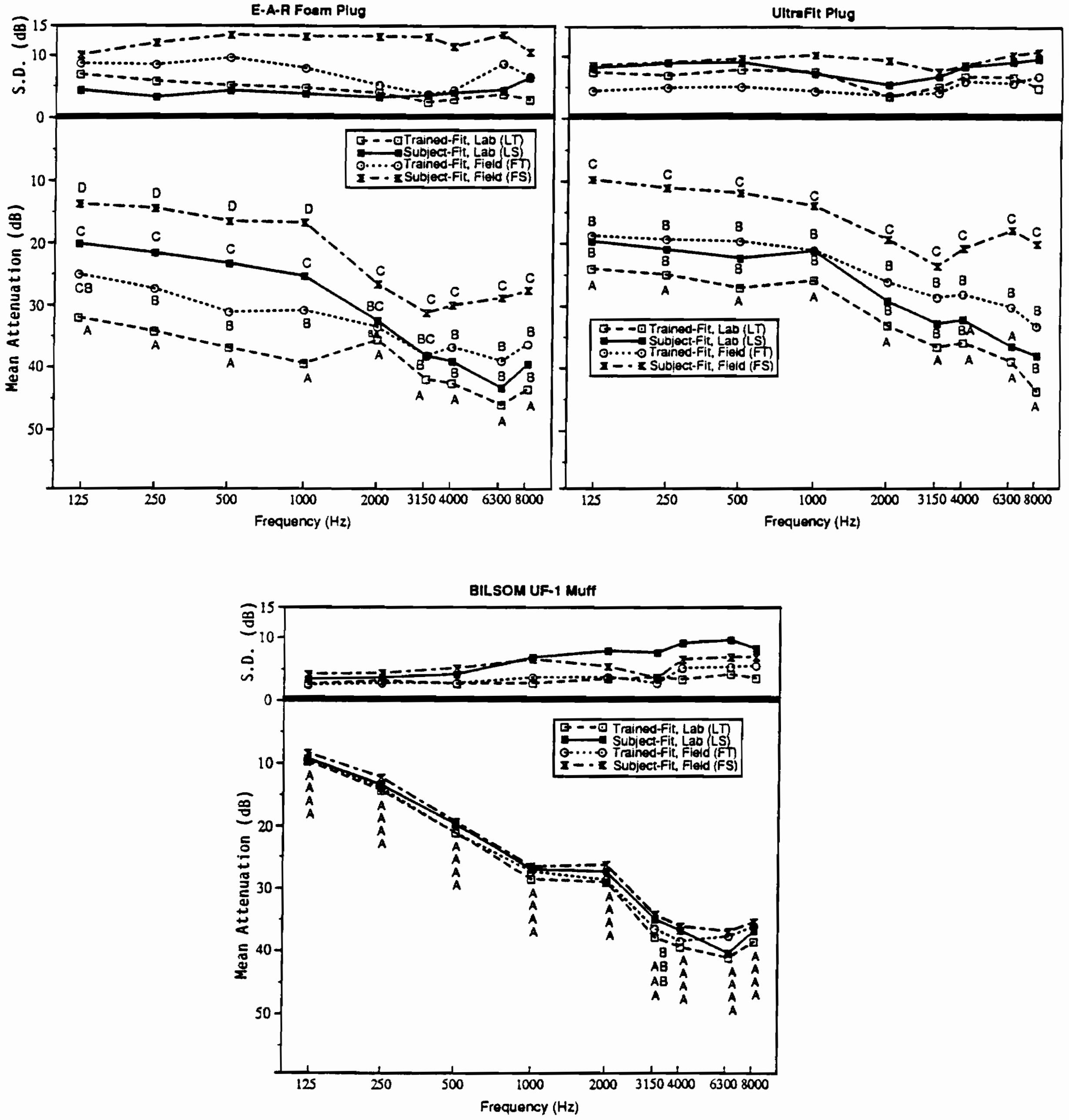
Attenuation Data Laboratory vs. Field Comparisons

For each of the 3 HPDs (E-A-R foam plug, Bilsom UF-1 muff, UltraFit premolded plug), which were common to the laboratory and field studies, pairwise comparisons, on an a priori basis, were made among 4 sets of attenuation data resulting from the 2 fitting procedures in the laboratory and field studies, namely, laboratory subject-fit (LS), laboratory trained-fit (LT), field subject-fit (FS), and field trained-fit (FT) data. (In collapsing field data, the 3 measurements for each fitting condition, over 3 weeks, were averaged.) Two-sample *t*-tests (Fallik and Brown, 1983) were applied for comparisons of the LS-FS, LS-FT, LT-FT, and LT-FS pairs, which were of primary interest in these analyses, while paired *t*-tests were appropriate for comparisons of the LS-LT and FS-FT pairs, which were of secondary interest, to examine further the fitting effect previously revealed in the ANOVA results. In summary, for each HPD of interest at each test frequency, 6 *t*-tests (4 two-sample and 2 paired) were performed in each of 3 comparison situations with different types of laboratory data: (1) overall laboratory data (mean of pre-/during-/post-task observations), (2) pre-task laboratory (just after initial fit, preceding work activity tasks and HPD wearing period), and (3) post-task laboratory data (after 2 hours of HPD wearing time and the activity tasks).

Attenuation Comparisons Using the Overall Laboratory Data

For each HPD, paired-comparisons using 6 *t*-tests at each of the 9 test frequencies were made between the 2 attenuation means in the LS-FS, LS-FT, LT-FT, and LT-FS pairs (using two-sample *t*-tests) and the LS-LT and FS-FT pairs (using paired *t*-tests). The test results are presented in Appendix O and are also illustrated in the 3 graph panels, one corresponding to each HPD, of Figure 23. From the graphs for the 2 earplugs, it is evident that laboratory and field protocols consistently yielded significantly different attenuation values. Direct comparisons between like-fitting conditions from the laboratory and the field, i.e., the LS-FS and LT-FT pairs, showed significant ($p < 0.05$) differences across test frequency with only 2 exceptions at 2000 and 3150 Hz for the foam plug.

For the foam plug, the mean attenuation difference between the laboratory and the field was slightly larger for the subject-fit condition than for the trained-fit condition, with averages of 8.6 dB and 6 dB across frequency, respectively. In terms of standard deviations (SDs), the difference was smaller for the trained-fit (an average of 2.7 dB across frequency) than for the subject-fit (an average of 8.1 dB across frequency). The closest agreement between the laboratory and field results occurred between the subject-fit in the laboratory and the trained-fit in the field, although the subject-fit mean (LS) results underestimated the field (FT) results by 4.9 to 7.8 dB at frequencies below 1000 Hz. Agreement improved at 2000 Hz and above. From



*Lab Data: Using Mean of Pre-/During-/Post-Task Observations
Field Data: Using Mean of 3 Weekly Observations

Figure 23. **Spectral attenuation comparisons of field data with overall laboratory simulation data.:** (Means with different letters in each frequency column are significantly different at $p < 0.05$).

Figure 23, it is quite apparent that no laboratory condition provided an accurate predictor of the field subject-fit (the typical field condition) protection levels, for either mean or SD data for the foam plug.

For the UltraFit plug, a similar trend was observed for the mean difference between laboratory and field protocols (a difference of 11.6 dB for the subject-fit and 7.3 dB for the trained-fit), but the SD values were in closer agreement. The subject-fit protocol in the laboratory (LS) yielded mean attenuation data which were not significantly different from the trained-fit field (FT) results at any frequency except 6300 Hz. However, as for the foam earplug, no laboratory condition provided reasonable predictions of the low attenuation achieved using subject-fit in the field.

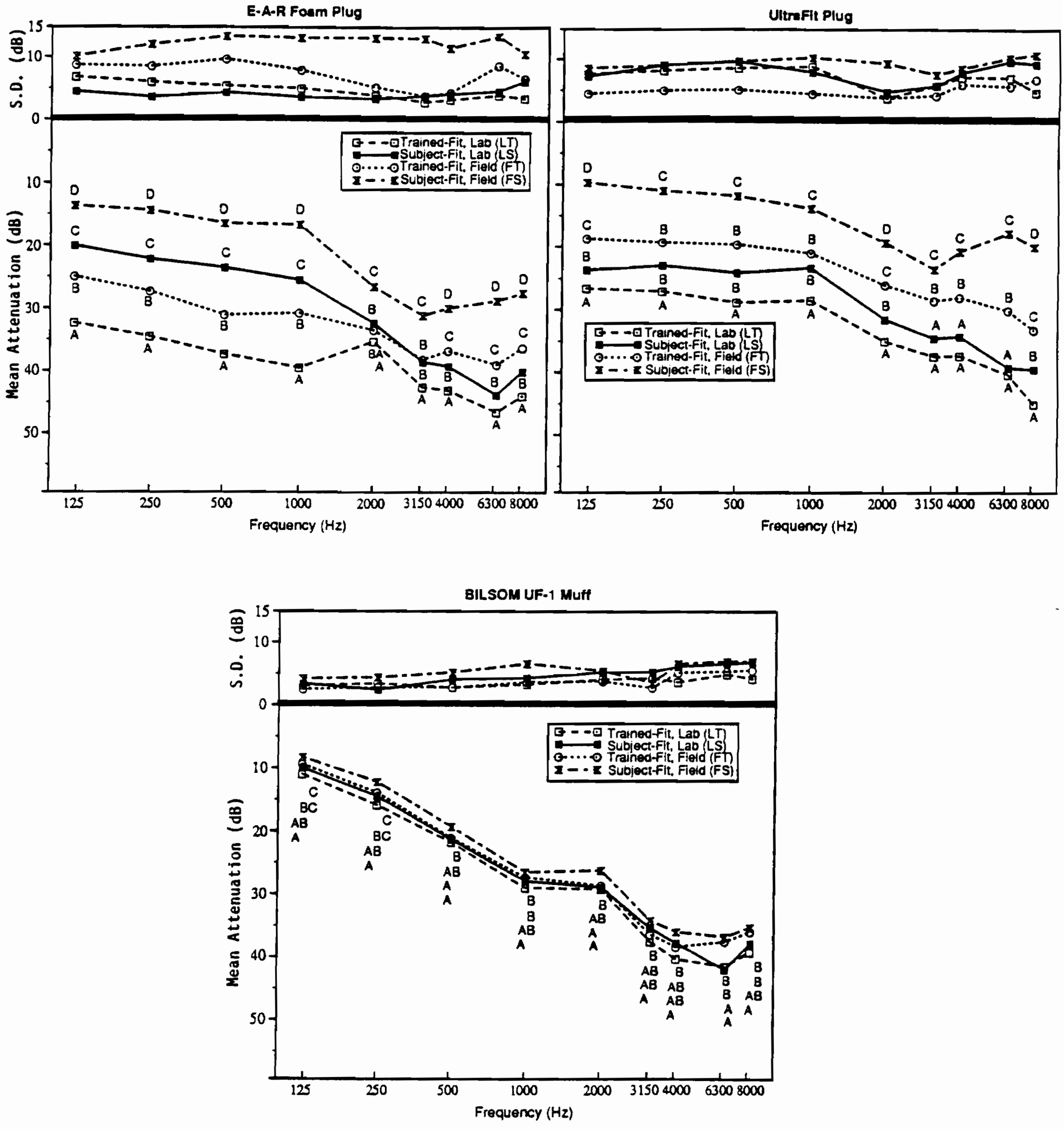
In contrast to the results for the earplugs, the earmuff showed close agreement between attenuation means and SD achieved under laboratory and field protocols. There were no statistically significant differences between any of the laboratory and field conditions, except for a single isolated and inexplicable difference between the trained-fit in the laboratory and the subject-fit in the field at 3150 Hz.

Attenuation Comparisons Using the Pre-task Laboratory Data

An important question was how much the field and laboratory data differed when the laboratory data were obtained immediately after HPD fitting, before the subject underwent the vigorous movement task. This condition most closely corresponded to that used in current ANSI HPD attenuation test protocols (ANSI S3.19-1974; ANSI S12.6-1984). Using the same *t*-test comparisons scheme as in the previous overall laboratory data analyses, the partitioned laboratory data (including only the pre-task portion of attenuation measurements) were compared to the field data. The resultant test statistics are presented in Appendix P, and HPD-specific results are illustrated in Figure 24.

For both earplugs, comparisons of the LS-FS and LT-FT pairs yielded consistently significant ($p < 0.05$) differences between the laboratory and the field over all test frequencies, with only one exception at 2000 Hz for the foam plug. The foam plug displayed an average attenuation advantage of 8.9 dB for the laboratory protocol over the field condition in the subject-fit procedure. However, the attenuation advantage of the laboratory over the field conditions was smaller (an average of 6.4 dB across frequency) in the trained-fit condition. The field protocol produced higher SDs than the laboratory: 8.0 dB and 2.5 dB for the subject-fit and the trained-fit conditions, respectively. As seen earlier in the overall laboratory data analyses (Figure 23), but with larger attenuation differences between the pre-task laboratory and the field data, the subject-fit laboratory data were most closely matched with the trained-fit field data. For frequencies below 2000 Hz, the LS results underestimated the FT values for the foam plug. Because the foam plug exhibited no work activity or wearing time effect in the laboratory study, the laboratory versus field differences did not change appreciably between the use of overall, pre-task, or, as will be seen, post-task laboratory data.

The UltraFit plug showed greater mean differences between the pre-task laboratory data and the field data than the foam plug: mean differences of 13 dB across frequency for the subject-fit and 9 dB for the trained-fit. However, the SD differences were similar: average SD differences of 1.4 and 1.8 dB for the subject-fit and the trained-fit, respectively. Also, this premolded plug achieved significantly ($p < 0.05$) more attenuation in the laboratory subject-fit (LS) condition than in the field trained-fit (FT) procedure over all test frequencies except 250 - 1000 Hz. An average (across the frequencies of 125 and 2000 - 8000 Hz) attenuation benefit of 6.4 dB was



*Lab Data: Using Mean of Pre-Task Observations
Field Data: Using Mean of 3 Weekly Observations

Figure 24. **Spectral attenuation comparisons of field data with pre-task laboratory simulation data.:** (Means with different letters in each frequency column are significantly different at $p < 0.05$).

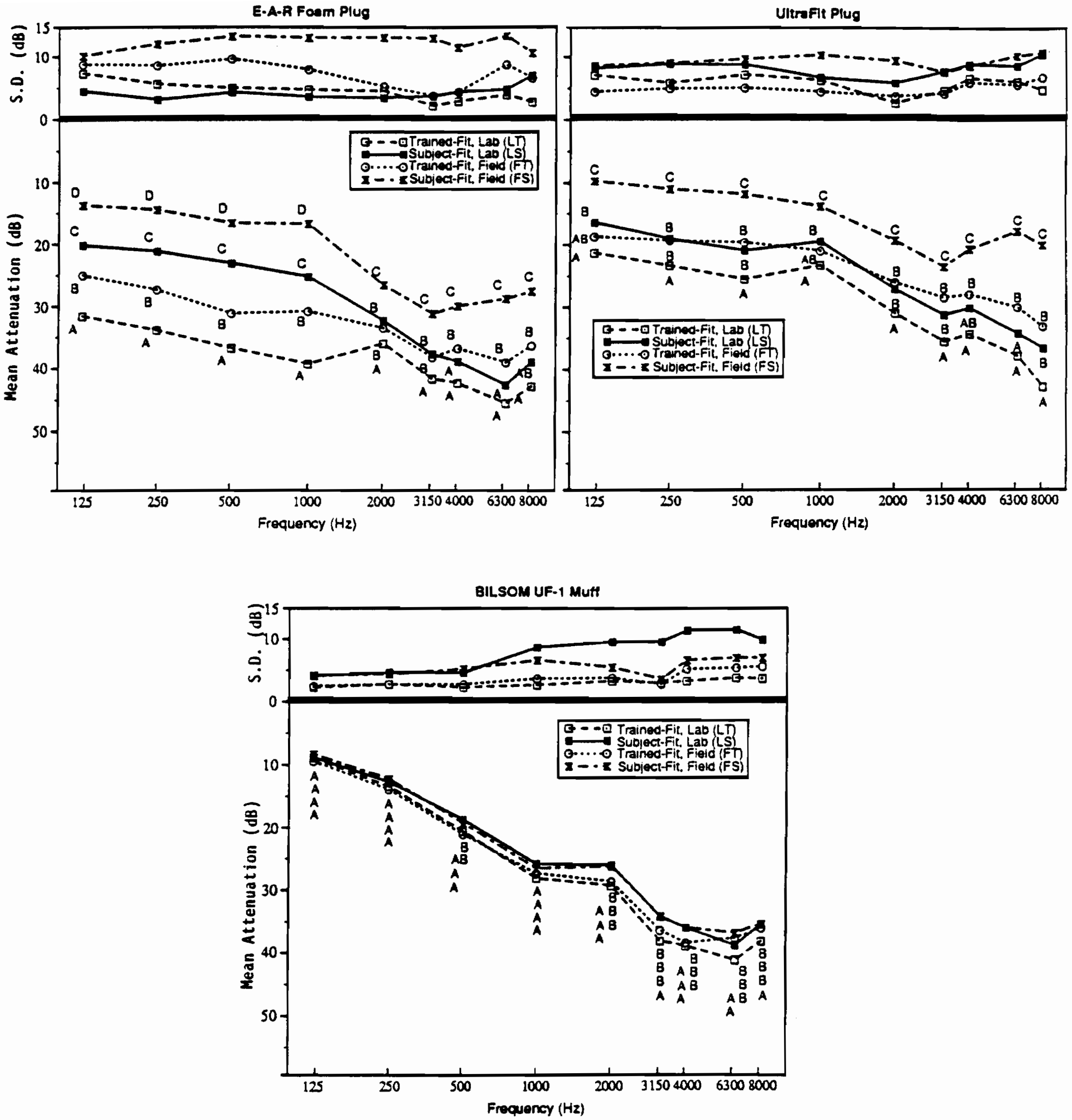
achieved under the LS condition over the FT condition. In essence, none of the laboratory conditions yielded reasonable estimates of field attenuation performance.

Unlike the previous comparison results with the overall laboratory data set, the earmuff showed significant, albeit small, differences between attenuation means in the LS-FS (at 125, 250, 500, 2000, and 6300 Hz) and the LT-FT (at 125, 250, 1000, 6300, and 8000 Hz) pairs. The mean differences between the 2 protocols were 2.3 dB and 1.8 dB for the subject-fit and the trained-fit conditions, respectively. For the earmuff, the subject-fit laboratory condition provided very similar mean and SD attenuation values to those obtained under trained-fit in the field, thus yielding an excellent prediction of actual protection afforded.

Attenuation Comparisons Using the Post-task Laboratory Data

It was hypothesized that if the laboratory work activity simulation elicited realistic work behaviors and posed sufficient stressors, then attenuation values obtained after the vigorous laboratory exercise tasks over the 2-hour HPD wearing period (i.e., the post-task laboratory data) might provide the best correspondence with field attenuation data obtained under similar fitting conditions in this study. The post-task laboratory data consistently yielded the lowest attenuation among the 3 partitioned pre-, during-, and post-task laboratory data sets. These post-task data were next compared to the field data using the same *t*-test comparison procedures as discussed previously. The comparison statistics are reported in Appendix Q, and the results for each HPD are depicted graphically in Figure 25.

The foam plug showed very similar post-task comparison results to those obtained previously with the pre-task laboratory data, implying that no significant pre- to post-task attenuation reduction was realized even after 2 hours of (laboratory)



*Lab Data: Using Mean of Post-Task Observations
Field Data: Using Mean of 3 Weekly Observations

Figure 25. Spectral attenuation comparisons of field data with post-task laboratory simulation data.: (Means with different letters in each frequency column are significantly different at $p < 0.05$).

wearing time while undergoing vigorous activities. Again, this was because once fit, the foam plug proved very resistant to slippage as a result of wearer movement (Casali and Park, 1990b). However, the results of the LS-FS and LT-FT comparisons clearly indicated that field and post-task laboratory data were significantly ($p < 0.05$) different from each other at all test frequencies. Laboratory attenuation values were still considerably higher (by an average of 8.3 dB for the subject-fit and 5.7 dB for the trained-fit) than the actual workplace attenuation achieved. Again, no laboratory condition yielded a reasonable estimate of subject-fit field performance. The closest approximation of the best (trained-fit) field performance was provided by the subject-fit condition in the laboratory, although the attenuation values produced were up to 9 dB lower than the trained-fit field values at the lower frequencies.

For the UltraFit plug, the comparison results were similar to those of the foam plug, but the laboratory versus field differences were less pronounced. Even after 2 hours of movement activities, attenuation obtained in the laboratory protocol was noticeably higher than that achieved in the field: an average of 10 dB and 6 dB for the subject-fit and the trained-fit conditions, respectively. However, the subject-fit laboratory data did provide reasonable agreement to the trained-fit field results at most frequencies.

In the case of the earmuff, laboratory and field results were found not to be significantly ($p > 0.05$) different in the LS-FS comparisons, but a few discrepancies were revealed in the LT-FT pair at 3150, 6300, and 8000 Hz. The differences across test frequency were less pronounced than those found in the previous comparison with the pre-task laboratory data; this result indicated that the earmuff attenuation decreased over the 2-hour laboratory wearing period. For both fitting procedures, the mean attenuation differences between the laboratory and field protocols were negligible (i.e., smaller than 1 dB), so the laboratory results were much better predictors of field protection for the earmuff than for either earplug. However, this does not necessarily mean that the laboratory work activity simulation truly mimicked the actual workplace effects on attenuation. Instead, the close agreement between laboratory and field results for the earmuff may be attributable to the fact that this earmuff, as well as many others, is easy and simple to fit. Also, earmuff attenuation might not be influenced as much by certain field factors as the plugs tested. This assumes, however, that the workers do not modify their earmuffs, such as by reverse-bending of headbands to relieve compression, and that they are maintained in good condition.

In sum, from the results of the attenuation data contrast, it can be concluded that attenuation obtained in the laboratory did not closely represent actual field attenuation, particularly for insert-type devices. The laboratory estimates of field attenuation for the earmuff were better predictors than for earplugs.

Attenuation Comparisons Using NRR

Due to the fact that the laboratory attenuation data did not have the necessary requirement of *3 trials* per subject to compute the typical NRR (as per ANSI S12.6-1984), comparisons of the laboratory versus field NRRs were not possible. Unlike the field data, which had 3 non-significantly ($p > 0.05$) different attenuation values over the 3-week time period and (hence could be treated as 3 separate trials per subject in NRR computation), the laboratory results showed that the 3 attenuation values over the 2-hour wearing time were significantly ($p < 0.05$) different. Therefore, those 3 separate data points were deemed unacceptable for consideration as 3 trials per subject, as required for NRR computation. Instead, the computed field NRR values for the 4 HPDs used in this study were compared to corresponding manufacturers′ reported (labeled) NRR data later in the ″DISCUSSION AND CONCLUSIONS″ section.

Comfort Data Laboratory vs. Field Comparisons

To determine the validity of estimating field HPD comfort performance via laboratory protocol (which used a relatively short wearing period of 2 hours), data sets from the 2 settings (laboratory and field) were compared using the 3 HPDs (E-A-R foam plug, UltraFit plug, and Bilsom UF-1 muff) common to both studies. Both comfort index (CI) and convenience rating data collected in each setting were used for comparison purposes.

Comparisons Using the Comfort Index Data

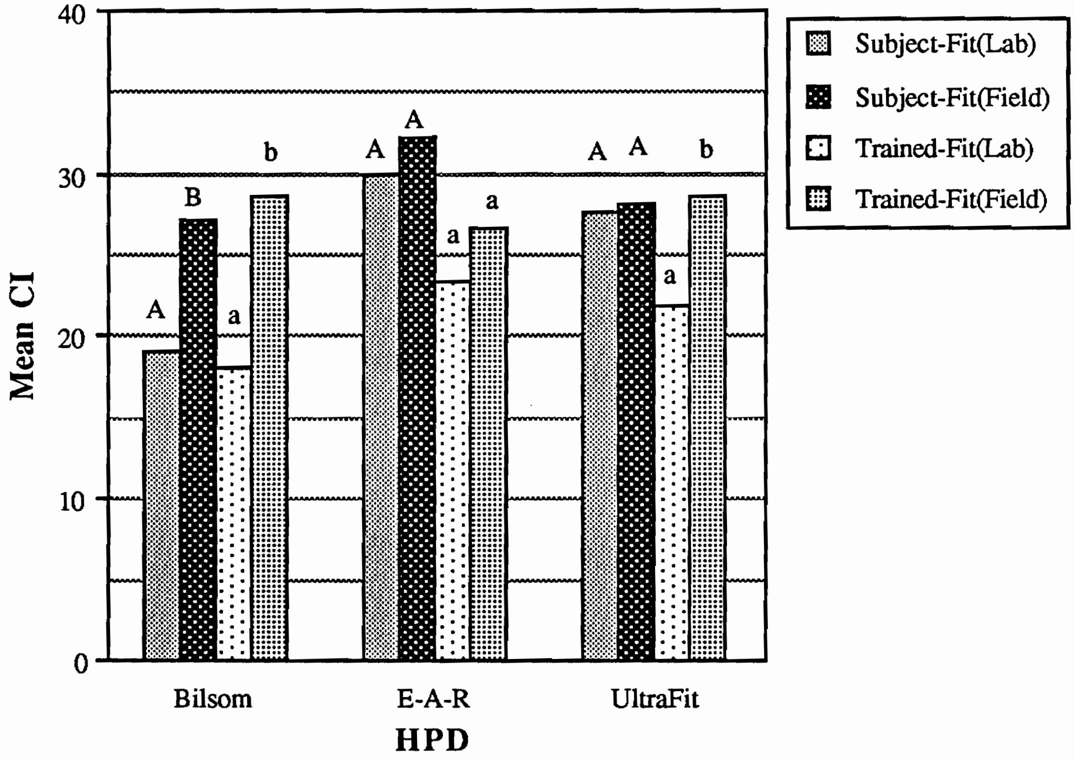
For laboratory versus field comparisons, only the comfort index (CI) data obtained after 2 hours of HPD wearing (i.e., post-task laboratory comfort data) were used as the laboratory data. These post-task laboratory data were believed to offer the most realistic representation of the field data in similar fashion to the post-task laboratory attenuation data discussed previously. To match both laboratory and field conditions as closely as possible, CI data from both settings were collapsed across the other factors to yield comparable data for each fitting procedure. In other words, the CI data in each fitting procedure for each HPD were compared to each other in the same manner as previously used in the attenuation data contrasts: (1) CI in the laboratory subject-fit versus CI in the field subject-fit and (2) CI in the laboratory trained-fit versus CI in the field trained-fit. Two sample *t*-tests were used to compare mean CI values for each fitting procedure and each HPD. The comparison results (based on the resultant *t* statistics summarized in Appendix R) are depicted in Figure 26.

Out of the 3 HPDs compared, 2 HPDs showed significant ($p < 0.05$) differences in comfort ratings between the laboratory and the field settings: in both fitting conditions for the Bilsom muff and in the trained-fit condition for the UltraFit plug. On the other hand, only the E-A-R foam plug results for either fitting condition were not significantly different between the laboratory and the field settings. It is also evident from Figure 26 that in the field setting, where HPDs are relied upon and comfort is of extreme importance, the differences in perceived comfort provided by the 3 HPDs were small.

Comparisons Using the Convenience Rating Data

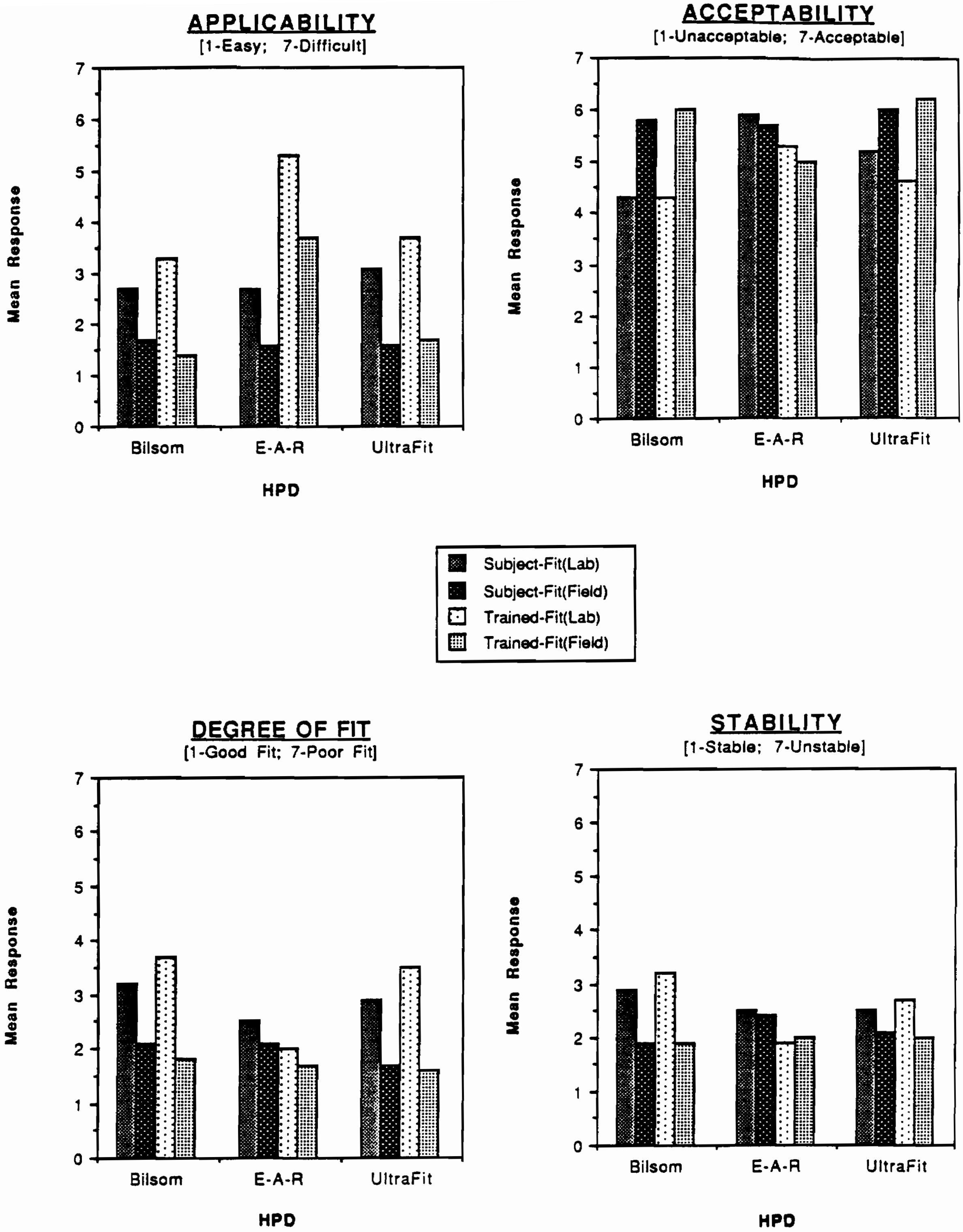
Another comparison was made using the convenience (i.e., overall experience) data. For each of the 8 scale dimensions used in the laboratory and field protocols, mean responses for each fitting procedure and each HPD were plotted (Figure 27) and descriptively compared. Noticeable differences between the laboratory and the field data were observed in each fitting procedure for the 4 dimensions: applicability (for all 3 HPDs), acceptability (for the Bilsom muff and the UltraFit plug), degree of fit (for the Bilsom muff and the UltraFit plug), and stability (for the Bilsom muff) scales.

From these laboratory versus field contrasts of comfort (and convenience) rating data, it must be concluded that HPD comfort (and convenience) ratings established in laboratory protocols which attempt to simulate the rigors of work may not always be relied upon to yield highly accurate predictions of user comfort and convenience under actual job conditions. The end-user in the field, who must live



Higher CI values indicate more comfort; HPDs described in text.

Figure 26. **Contrast of laboratory and field comfort index data:** (Means with different letters [upper characters for the subject-fit and lower characters for the trained-fit comparisons] for each HPD column are significantly different at $p < 0.05$).


APPLICABILITY [1-Easy; 7-Difficult]

ACCEPTABILITY [1-Unacceptable; 7-Acceptable]

DEGREE OF FIT [1-Good Fit; 7-Poor Fit]

STABILITY [1-Stable; 7-Unstable]

Figure 27. Contrast of laboratory and field data mean response plots of fitting procedure for each HPD (described in text) on each convenience rating scale.

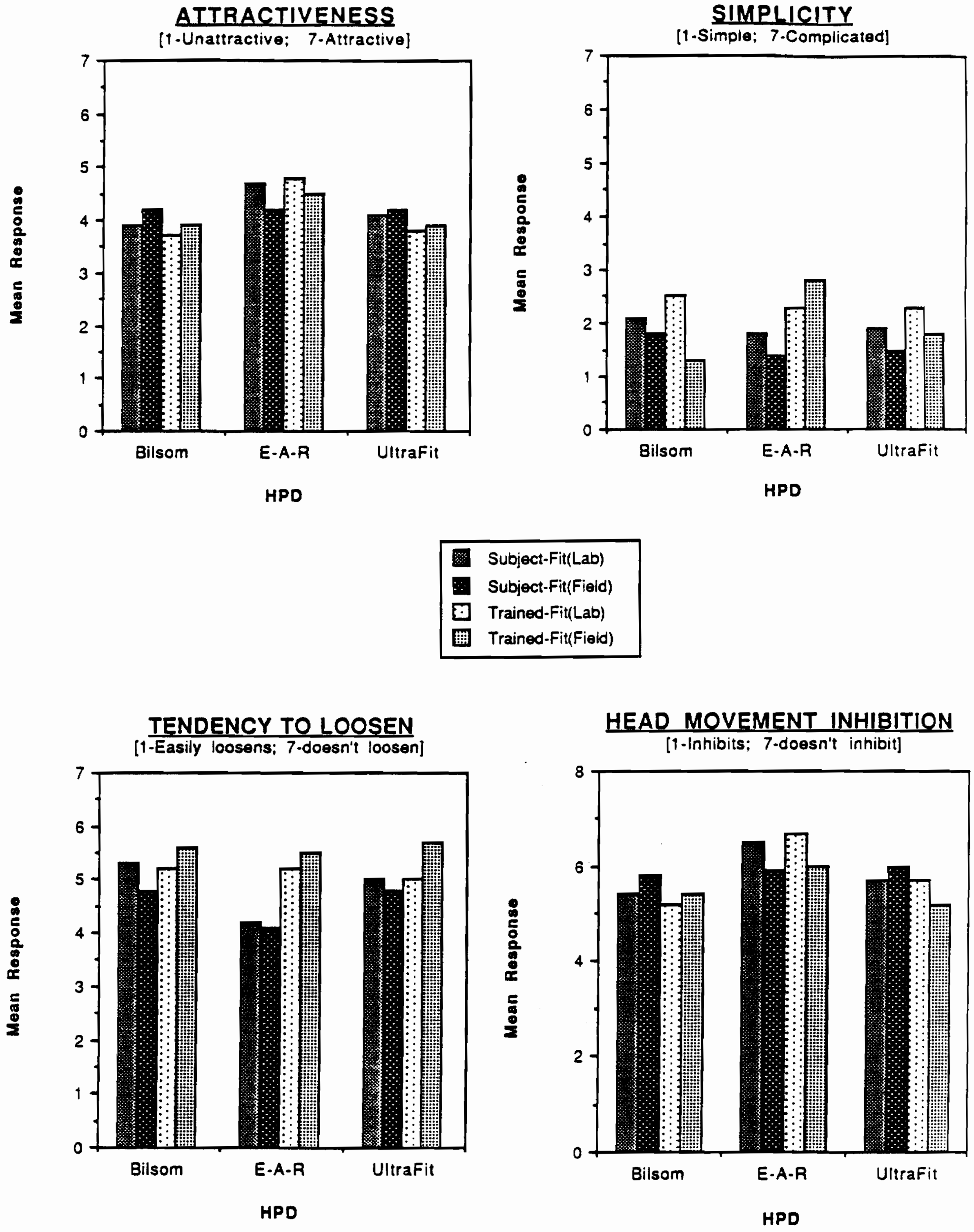


Figure 27. Contrast of laboratory and field data mean response plots of fitting procedures for each HPD (described in text) on each convenience rating scale (Continued).

with an HPD on a daily basis during work, provides the ultimate test of device acceptance.

DISCUSSION AND CONCLUSIONS

The major objective of this field study, to determine the field performance (noise attenuation and comfort) achieved with 2 earplugs, an earmuff, and an ear canal cap as affected by different levels of HPD fitting procedure and time of use, was met. Perhaps more importantly, the results indicated that laboratory simulation tests designed to mimic field influences on attenuation may be expected to yield reasonable estimates of field performance for only certain HPDs. Laboratory versus field attenuation agreement under identical fitting conditions was good for the earmuff, but not for either earplug tested. In terms of comfort, only the foam earplug showed no significant difference between the laboratory and the field protocols. The ensuing discussion focuses on these significant findings in 2 categories: attenuation and comfort. Implications of the results from the laboratory versus field contrasts are also addressed.

Attenuation Considerations

The field attenuation results demonstrated that both insert-type HPDs (earplugs) offered significantly more attenuation in the trained-fit condition than in the subject-fit condition. Also, attenuation provided by the UltraFit earplug changed noticeably over the 3-week period at the lower frequencies of 125 - 500 Hz, with significant attenuation loss over time under the subject-fit condition. A discussion of the fundamental attenuation results follows.

Importance of proper HPD fitting

From the results of the significant fitting procedure effects (Figures 7, 9, and 11), it is clear that with brief interactive training for proper HPD fitting, the workers markedly improved their protection over that obtained with minimal fitting information (i.e., the use of only manufacturer's package instructions). Training and practice in HPD fitting with visual and verbal feedback was believed to be an essential key for attenuation improvement. However, the benefit of this training effect was highly device-dependent, i.e., consistently improved attenuation for the earplug HPDs, but not for the earmuff or canal cap (Figure 9). The E-A-R foam plug exhibited a much more pronounced fitting effect than the UltraFit plug, particularly at frequencies of 1000 Hz and below: averages of 12.0 dB (across frequencies of 125 - 1000, 6300, and 8000 Hz) and 9.6 dB of attenuation improvements due to training were achieved by the foam and the UltraFit plugs, respectively. This implies that that the premolded UltraFit plug is a simpler device to fit than the foam plug. The patterns of these 2 earplugs' attenuation results generally agree with those found in the laboratory (Casali and Park, 1990a), which showed a strong low-frequency fitting procedure effect. This low-frequency fitting effect, as supported theoretically (e.g., Zwislocki, 1957) and empirically (e.g., Berger, 1982a), may be due primarily to lowered earplug stiffness and reduced effective mass resulting from poor fitting (i.e., shallow insertion and less contact with the canal walls) in the subject-fit condition. The attenuation improvement with training also has the important benefit that protection from the particularly hazardous high frequencies is enhanced.

On the other hand, field attenuation for the earmuff and ear canal cap was relatively insensitive to the fitting effect, and this finding corroborates previous laboratory-based results on similar HPDs (e.g., Casali and Lam, 1986a; Riko and

Alberti, 1982). Fitting procedures for earmuffs and most canal cap devices are typically simpler and more straightforward than those for certain earplugs, especially user-molded, foam plugs such as the E-A-R foam plug, which require more complex manipulation and insertion procedures. For proper insertion of earplug HPDs, the pinna of the ear needs to be pulled upward and outward to straighten the ear canal on most individuals, although this is not the case for earmuffs nor most ear canal caps. This is particularly true in the case of the user-molded, slow-recovery foam earplugs, which must be compressed, rolled into a small diameter cylinder, and inserted promptly before they expand.

In addition, the results illustrated in Figure 7 further support the importance of training for proper HPD fitting. At 2000 Hz and below, attenuation achieved with subject-fit consistently decreased over the 3-week period, whereas the workers who received training improved their protection at least 1 week thereafter. The standard deviation (SD) results also demonstrated the benefit of training (Figures 7, 9, and 11). In all cases, the trained-fit condition resulted in smaller SDs, which implies an improved control on HPD placement over that in the subject-fit condition, especially for the earplugs.

In summary, this research along with previous studies (e.g., Casali and Park, 1990a) clearly showed that training workers to properly fit HPDs is important. When the workers rely solely on manufacturers' package instructions to wear HPDs, they often fit them improperly and/or incompletely. This may be because manufacturers' on-package instructions (e.g., see Appendix E) are often brief, hard to read, and limited due to the small printing space available, thus they may go unnoticed by the workers. Some instructions may be difficult to understand, particularly by the inexperienced HPD user. Therefore, comprehensive, easy-to-understand, field-usable instructions for each hearing protector model are required to enhance noise protection. As a typical guideline, Berger (1988a) enumerates several generic tips for fitting several different types of HPDs. Furthermore, video-taped instructional programs available from a few HPD manufacturers may also help workers in fitting HPDs in the field. After all, training is an essential part of a successful industrial hearing conservation program.

Attenuation change over time period of HPD use

Although a general trend of attenuation change over the 3-week period of HPD use (i.e., time of use main effect) was not significant in the overall ANOVA, it is evident that HPD attenuation changed under certain conditions. When collapsed across HPDs, the data shown in Figure 7 demonstrate that the subject-fit condition was associated with an average attenuation *decrease* (over the 3-week period) of 3 dB across 125 - 2000 Hz, while the trained-fit procedure offered an average attenuation *increase* of 2 dB across the same frequency spectrum. For the same frequency range, the results in Figure 6 show device-specific attenuation changes over time under the different fitting conditions. Under subject-fit, the premolded UltraFit plug lost attenuation (an average of 8 dB across 125 - 2000 Hz) over the 3-week period, and this result is also supported by the UltraFit data illustrated in Figure 8: an average decrease of 4 dB over the same period when data are collapsed across fitting procedures. On the other hand, the foam plug under subject-fit shows relatively stable attenuation over the 3-week period (Figure 6). However, with training, the foam plug's attenuation increased by an average of 2.3 dB (across 125 - 2000 Hz) over the 3-week period, whereas the UltraFit did not exhibit any significant increase in training benefit over the same period. It appears that with proper initial interactive user training, the protection of certain earplugs (e.g., the foam plugs) can be effectively improved over relatively short periods of time as workers gain experience with the devices.

Overall field attenuation achieved by the various HPDs

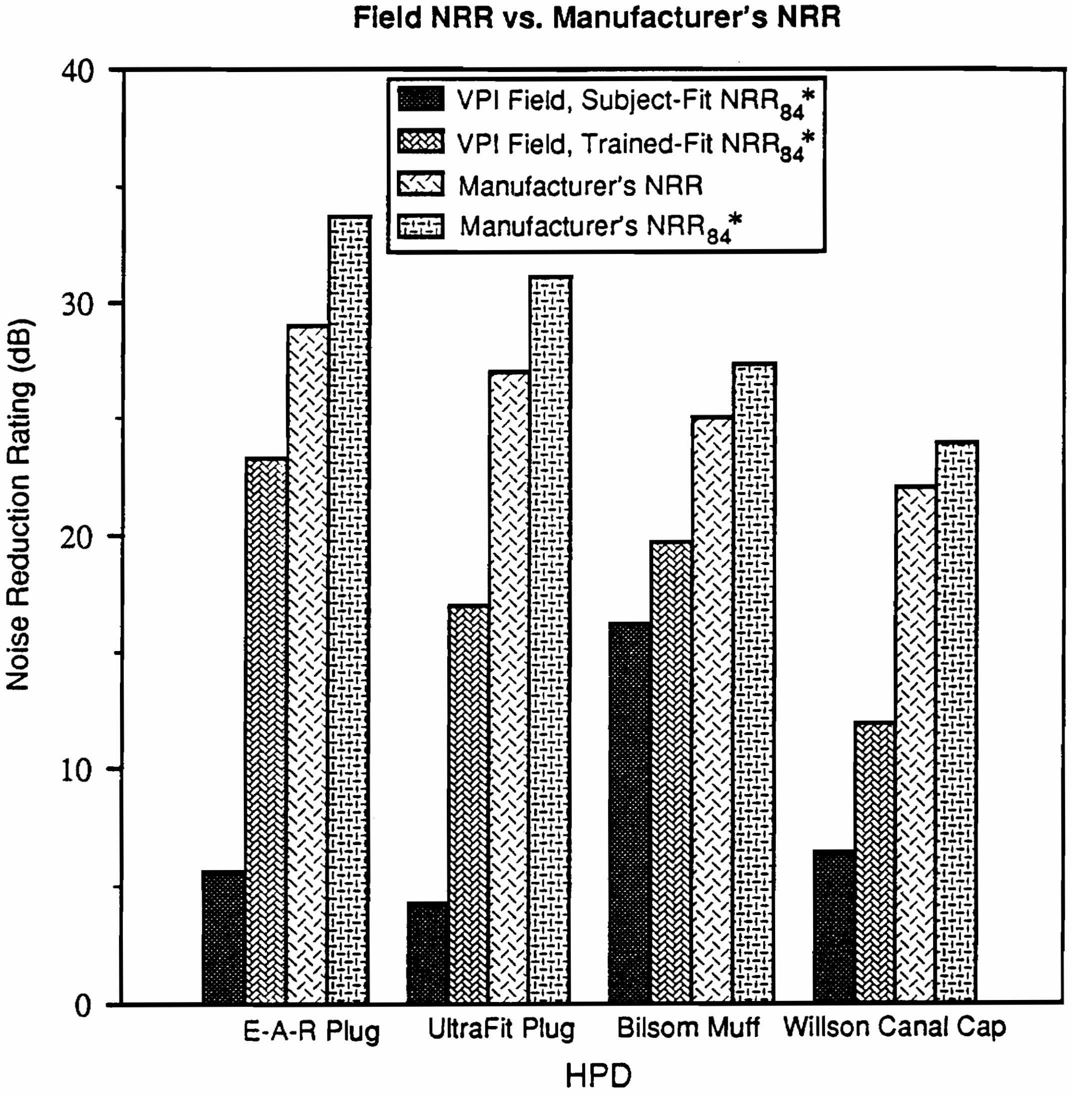
Although the field attenuation performance of the 4 HPDs has now been compared under the various experimental conditions, overall performance may be addressed by collapsing the data across the variables of fitting procedure and time of use. As expected, overall real-world attenuation achieved by the 4 HPDs showed significant frequency-specific difference (Figure 10). These collapsed data did not indicate such a clear attenuation performance ordering as the oft-claimed workers' misconception of earmuffs' attenuation superiority over earplugs in the field. Rather, the data generally support a typical earplugs versus earmuffs result: low-frequency strength for earplugs and high-frequency strength for earmuffs. As evidence, the highest attenuation was achieved by the foam earplug at the lower frequencies of 500 Hz and below and by the earmuff at the higher frequencies of 3150 Hz and above. Therefore, selective HPD application should be considered with the spectral characteristics of the noise environment in mind. Of course, these results are based on a very limited sample of earplugs and earmuffs.

Attenuation comparisons with manufacturers' and other field data

Field NRR comparisons with manufacturers' rating

Field performance, calculated as NRR_{84}, of the 4 HPDs used in the Virginia Tech (denoted by VPI) field study was compared to the manufacturers' laboratory-based NRRs. The real-world NRRs were computed for each HPD (as presented both in the subject-fit NRR_{84} and the trained-fit NRR_{84} columns in Table 26) and illustrated in Figure 28, along with each corresponding manufacturer's NRR and computed NRR_{84} values. All HPDs show large discrepancies in a conservative comparison between the VPI field subject-fit NRR_{84} which incorporates only a 1 standard deviation correction) and the manufacturer's NRR (which incorporates a 2 standard deviation correction). The field versus laboratory differences are largest for the foam plug (by 23.4 dB), followed by the premolded UltraFit (by 22.7 dB), the Willson canal cap (by 15.6 dB), and the Bilsom muff (by 8.8 dB). Of course, when the computed manufacturers' NRR_{84} values (which yield higher ratings than the typical reported NRR data) were compared to VPI field subject-fit NRR_{84} values, overestimation (by the manufacturers' data) was even much worse: 28.1, 26.8, 17.5, and 11.1 dB for the foam plug, the premolded plug, the canal cap, and the muff, respectively in descending order. Although foam plugs have been reported to have the highest field attenuation of any earplugs used (Berger, 1988b), the current data for the foam plug yielded a field subject-fit NRR_{84} of only 5.6 dB in the subject-fit condition (due primarily to large standard deviations, as evidenced in Figures 9 and 10). This may indicate that the subject-fit and random worker retrieval protocol in the VPI field study constitutes a near-worst case among the field studies, based on previous field NRR results summarized by Berger (1983), which ranged from NRR_{84} values of 5 to 19 dB for the foam plugs used in several field studies.

Although the NRR_{84} increased by 3.5 (for the Bilsom muff) to 17.7 dB (for the E-A-R plug) due to training, the trained-fit NRR_{84} values were still considerably lower than the corresponding manufacturers' NRR data. Differences between the trained-fit NRR_{84} and the corresponding manufacturers' NRR values were 5.3, 5.7, 10.0, and 10.1 dB for the Bilsom muff, the E-A-R foam plug, the UltraFit plug, and the Willson canal cap, respectively in ascending order. This result implies that a certain derating



*See text for explanation.

Figure 28. **Comparison of Virginia Tech (VPI) field NRR_{84} scores with manufacturers' NRR values.**

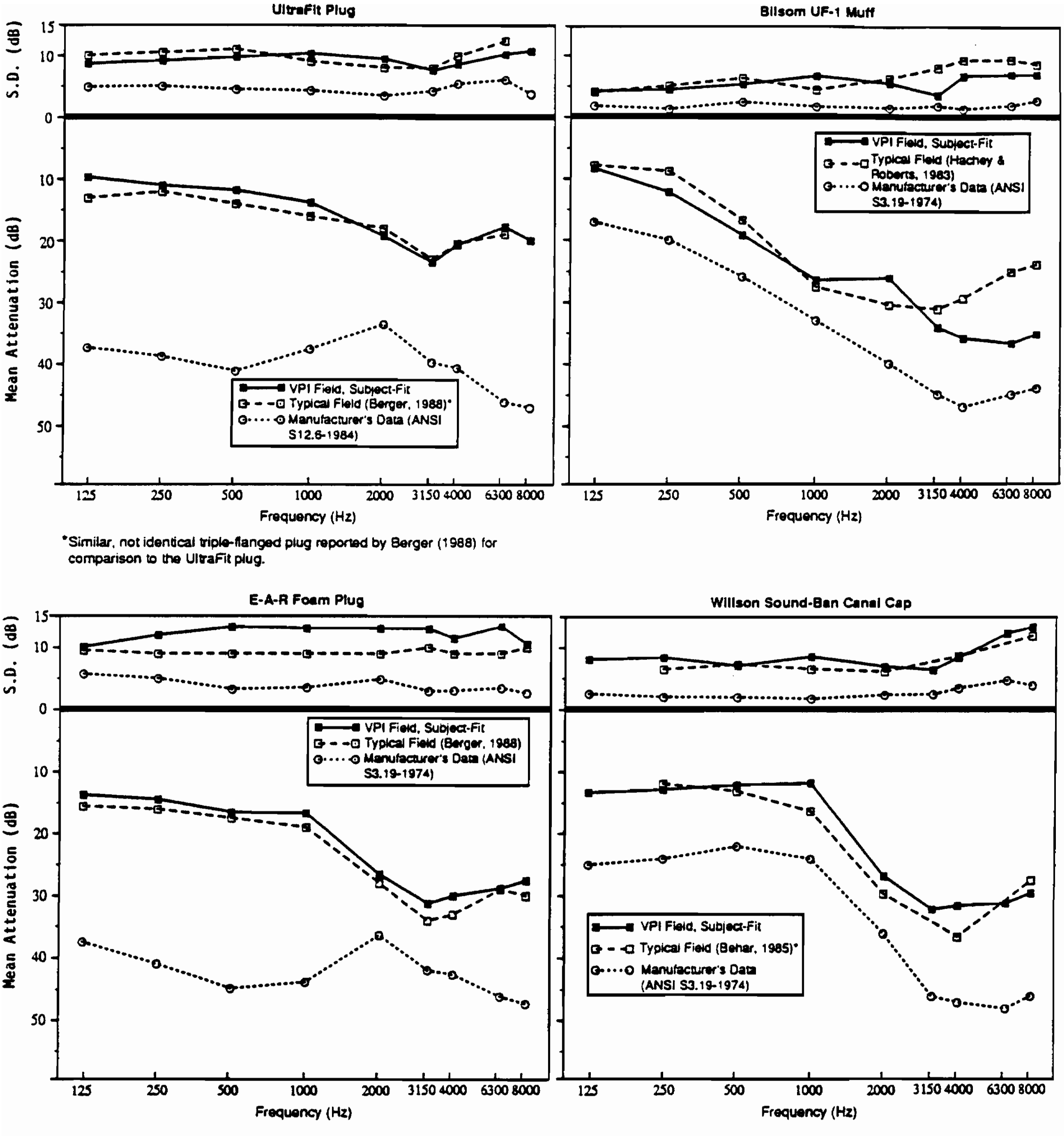
scheme is necessary when using the current manufacturers' NRR values for estimating a broadband noise protection in the field, even though workers are trained to fit HPDs appropriately.

Spectral attenuation comparisons with other field and manufacturers' data

The spectral attenuation results of the VPI field study were compared with those of other typical field studies. Four separate plots in Figure 29 compare the subject-fit (which can be considered as a typical field fitting) frequency-specific attenuation data of the VPI field study to results of other field studies and also to each HPD manufacturer's reported spectral data.

The typical field data used for comparisons of the foam plug are the data resulting from averaging the results of 10 field studies (Berger, 1988b). As illustrated in Figure 29, the VPI field study's mean attenuation values fall close to the typical field data, though yielding about 2 dB smaller attenuation across frequency than the typical results. In terms of standard deviations (SDs), particularly for the foam plug, the VPI field study provided consistently larger SDs than the others (which typically employed multiple tests on single device), perhaps due to the inconsistent fit produced in the subject-fit condition and the completely random, unannounced retrieval of the workers for testing. When compared to the manufacturer's data, the VPI field mean attenuation values fall far below the reported on-package data, as would be expected: the attenuation difference ranged from 9.7 to 28.3 dB, depending on the frequency, while SDs of the VPI field study are greater than those labeled by the manufacturer.

For the triple-flanged UltraFit plug, the typical field results used in Figure 29 were from a study which evaluated "a similar 3-flanged earplug" (Berger, 1988b, p. 27), the exact model of which was unspecified. The VPI field study results agree



UltraFit Plug

Bilsom UF-1 Muff

E-A-R Foam Plug

Willson Sound-Ban Canal Cap

*Similar, not identical triple-flanged plug reported by Berger (1988) for comparison to the UltraFit plug.

*As per pseudo ANSI S3.19-1974 due to the test site problems.

Figure 29. Comparison of Virginia Tech (VPI) field spectral attenuation data with other field and manufacturers' data.

closely (in both mean and SD attenuation) with the other field data. Also, the results of comparisons with the manufacturer's data indicate that the attenuation differences between the manufacturer and the field values are larger than those of the foam plug: from 14.2 to 29.3 dB across frequency.

Turning to the Bilsom earmuff, a study by Hachey and Roberts (1983) provided the only available field data for comparison purposes (Figure 29). According to the results, both field studies generally yield similar attenuation values across frequency with exceptions at 4000 Hz and above, whereas the VPI study's means are higher and SDs slightly lower. When compared to the VPI field results, the manufacturer's data overestimate the field attenuation by an average of 9 dB across the spectrum, with consistently smaller SDs.

Finally, field attenuation performance of the Willson canal cap used in the VPI study was compared to that of Behar (1985), the only known source for comparable field data for that device. The comparison results (Figure 29) demonstrate that both sets of field attenuation data were in generally close agreement. In comparison with the manufacturer's data, the overestimation in attenuation is an average of 13 dB across the spectrum. The SDs of the VPI field study are again considerably larger than those reported by the manufacturer.

Prediction of overall protection using single test band attenuation

Currently, it is widely accepted that the most accurate method of measuring HPD attenuation is to apply the REAT procedure (as per ANSI S12.6-1984 or ANSI S3.19-1974), which uses 9 1/3-octave bands for testing. But when the information that is required pertains to actual workers who are wearing HPDs in a hearing conservation program, such a procedure may be unwieldy and impractical. This fact leads to the need for a simple, quick procedure to estimate the overall HPD protection level. The results of regression analyses (Tables 28 through 31 and Figures 12 through 19) in this field study suggest that field attenuation measurements could be limited to only one frequency (i.e., 500 Hz or 1000 Hz) to provide an accurate prediction of overall field noise protection, NRR_{PS}.

Among the major advantages of using single-frequency attenuation data for this prediction purpose are the speed, practicality, and repeatability of HPD testing on individual users in the field. If such a single-frequency test is valid, it can be used to ascertain the actual protection levels that workers are realizing in the workplace environment. The speed/practicality of single-frequency testing probably compensates for any small benefits in accuracy that might be achieved via testing 9 spectral frequencies. Assuming that a single attenuation measurement (i.e., occluded and unoccluded thresholds) at each test frequency requires about 4 minutes, then testing the additional 8 frequencies would extend the total time for each test by at least 30 minutes. This testing period will be even longer if several trials are repeated, as is often the case with untrained subjects. Thus, in a practical sense, using only one frequency for protection estimation purposes would save a considerable amount of testing time in the long run and enable individual workers' protection levels to be acoustically verified. Another benefit of this single-frequency approach is that it permits repeat testing to improve the precision of test results. Repeating threshold trials at a single frequency should reduce the variability of measurements, which is typically large in field data.

Based strictly on regression statistics (e.g., correlation coefficient, slope, and intercept), there is no distinct clear-cut advantage of one test band (500 Hz or 1000 Hz) over the other for NRR_{PS} prediction across all HPDs (Table 27). However, when specifically different fitting conditions are considered, the 500 Hz data provided slightly better prediction under subject-fit, as evidenced in both the regression statistics (Table 28) and the mean differences between the predictor and the predicted values (Table 30). However, this fitting procedure effect was not apparent in the NRR_{PS} predictions from the 1000 Hz data, except for the foam plug. In general, the predictions using both frequencies were reasonable, and either frequency could be used to predict employee broadband protection in the field. Although the results of prediction were device- and fitting procedure-dependent (Figures 12 through 19), both predictor (i.e., attenuation at 500 or 1000 Hz) and predicted values (i.e., NRR_{PS}) are in good agreement in a practical sense: overall, mean differences between the predictor and the predicted values ranged from 0.9 dB (for the UltraFit plug) to 1.7 dB (for the E-A-R plug), all of which were within only a 2-dB prediction error (Tables 30 and 31), with only one exception for the Bilsom muff (Table 31). Furthermore, under subject-fit, the prediction from the 500 Hz data was accomplished even more accurately: mean prediction errors for 4 HPDs were all about 1 dB or less (Table 30), which is negligible in a practical/acoustical sense. This result has a very significant implication in regard to estimation of overall protection in the field. That is, since the subject-fit condition used in this study (which represents the common HPD fitting situation in the industrial workplace) accurately predicted the field NRR_{PS}, reliable estimation of overall protection for each individual can easily be made in the field on the basis of a quick, single-frequency test.

In addition, prediction intervals (PIs) based on the resultant regressions, provided minimum (conservative) acceptable protection levels from each individual single-frequency attenuation measurement. Again, excellent prediction results were obtained with the subject-fit data. In practice, it would be desirable to measure attenuation (i.e., via subject-fit conditions) on each individual worker at one time on a single-frequency, and to compare the measured value to a minimum acceptable level given by the lower bound on the prediction interval.

In conclusion, based on the prediction results, estimating overall field noise protection (e.g., NRR_{PS}) by single-frequency (500 or 1000 Hz) data is practical, reasonably accurate, and feasible. Therefore, this single-test band measurement on individual workers would constitute an excellent, quick method for monitoring HPD effectiveness in the field. The only requirement for this simple approach is that the REAT measurements be obtained in an audiometric booth or other suitably quiet test space in the field. As Berger (1988c) and Webster et al. (1956) suggested, pure-tones (rather than 1/3-octave band signals) might be used for attenuation testing without losing significant accuracy in test results. Hence, pure-tone industrial audiometers, which are readily available in the field, might alternatively be used for attenuation measurements with the additional benefits of availability, lower cost, and ease of use. However, more work needs to be done to determine if the prediction results obtained using pure-tones provide adequate accuracy. Furthermore, more research should be directed toward determining if audiometric headphones with pure-tone audiometers can substitute for the sound field conditions.

Comfort Considerations

For the comfort index (CI) data analysis, the CI (a single-number comfort measure) was first developed by the correlational procedure and the criteria discussed in the "RESULTS: COMFORT DATA" section. From the subsequent parametric statistical procedures, the fitting procedure factor was found to significantly influence user-rated comfort achieved with the foam earplug, but this effect was not pronounced for the other devices. Descriptive convenience rating results also supported noticeable fitting procedure effects for the foam earplug. The fundamental results from comfort and convenience rating data are discussed in the ensuing sections.

Significance of fitting procedure effect on comfort

From the results of the field comfort index (CI) data, it is evident that user comfort ratings for certain earplugs, particularly user-molded foam earplugs, may change depending on the fitting procedure used. The comfort afforded by the E-A-R foam plug was significantly higher under the subject-fit condition than under the trained-fit condition (Figure 20). This result agrees with other reports (e.g., Berger, 1988b) in that when plugs are fitted to obtain high attenuation, they may be inserted more deeply and thus induce more discomfort than when receiving shallow insertion. Based on anecdotal observations, subjects often appeared to wear their HPDs in the most comfortable fashion in the subject-fit condition, without regard to obtaining an effective noise seal. For example, subjects often did not insert the earplugs deeply enough to obtain a long cylinder of plug-to-canal wall contact. This was most frequently true for the slow-recovery foam plug in the subject-fit condition because the subjects simply did not sufficiently roll the foam plug, pull the pinna to straighten the ear canal, and insert the plug promptly and properly. However, once they grasped the correct insertion technique in the trained-fit condition, most could insert the foam plug much more deeply than before, hence achieving noticeably higher attenuation (Casali and Park, 1990a), but again less comfort. As Brown-Rothwell (1986) explains, major contributory factors for earplug comfort include friction and tissue shearing at the earplug interface with the canal walls, although the exact mechanism of discomfort probably involves more factors. Based on the convenience (i.e., overall experience) rating results, noticeable fitting influences for the foam plug were also observed in 3 convenience dimensions: applicability, tendency to loosen, and head movement inhibition (Figure 22). When donned under subject-fit, the user-molded foam plug was found to be significantly easier to apply, more easily loosened, and more inhibited by head movement than under trained fitting.

On the other hand, fitting procedure did not significantly affect perceptions of comfort for the earmuff and the canal cap devices. The insensitivity of the muff and the canal cap devices to the fitting effect was borne out in field attenuation data, as previously discussed. This is likely due to the fact that earmuffs and canal caps are generally more straightforward and easier to don than earplug devices.

Comfort achieved with different HPDs

When collapsed across other variables, the field comfort showed a significant difference in perceived comfort only between the canal cap and the other 3 HPDs (Figure 21). According to the overall experience (convenience) ratings, the field subjects seemed to prefer the premolded UltraFit plug on the basis of acceptability and degree of fit (Figure 22). When no training was given (i.e., under subject-fit), the field subjects rated the foam plug as equally acceptable and attractive to the premolded plug. But when asked to follow the proper technique (i.e., under trained-fit), they rated the foam plug as less acceptable.

The canal cap device had the highest reported discomfort in field use (Figure 21) and was also judged as the least acceptable and least attractive HPD (Figure 22). However, it should be noted that this type of HPD is perhaps most amenable to intermittent use in situations where users need to don and doff their

HPDs quickly and frequently. Thus, canal caps are quite useful for those who must frequently go in and out of noisy areas.

Validation of the Laboratory Simulation Study

To determine the accuracy and validity of estimating field HPD performance (both attenuation and comfort) via a laboratory simulation protocol (Park, 1989), data sets from the 2 settings (laboratory versus field) were compared using the 3 HPDs (E-A-R foam plug, UltraFit flanged plug, and Bilsom UF-1 muff) common to both studies.

The attenuation results of the field study were first compared to the laboratory attenuation data, partitioned in 3 ways, as discussed previously. As depicted in Figures 23 through 25, the 2 earplugs used for comparison showed consistently higher mean attenuation under the laboratory than the field experimental protocols, indicating that the laboratory work activity simulation could not sufficiently account for all of the field influences. Comparisons with the worst-case (i.e., post-task) laboratory data, which were believed to offer the most realistic representation, still demonstrated significant differences between the 2 settings (Figure 25). Averages of 8.3 dB (for the subject-fit) and 5.7 dB (for the trained-fit) mean attenuation differences were observed for the foam plug; 10 dB and 6 dB were found for the UltraFit. Although the earmuff's attenuation generally provided good agreement between the laboratory and the field settings, the results from the 2 earplug devices strongly suggest that laboratory simulation data cannot be used as an accurate indicator of real-world attenuation measures.

By the same token, the laboratory comfort index (CI) data obtained after 2 hours of HPD wearing (i.e., post-task laboratory CI data) were compared to the field

CI data. Based on the comparison results (Figure 26), 2 out of the 3 HPDs demonstrated that both laboratory and field protocols did not yield reasonably close agreement in perceived user comfort. Also, it is noted from Figure 26 that in the field setting where comfort is of practical importance to the effective use of HPDs on the job, the differences in user-rated comfort among the 3 HPDs were small. Thus, HPD selection (within this sample) based solely on comfort may be up to the personal preference of the end-user in the field. On the basis of the convenience rating comparisons, for at least 2 HPDs noticeable differences were again observed between the laboratory and the field protocols in 4 convenience dimensions out of the 8 used (Figure 27): applicability, acceptability, degree of fit, and stability.

SUMMARY AND RECOMMENDATIONS

Summary of the Current Study

Major findings from the current field research are summarized as follows:

1. The earplugs were highly susceptible to fitting procedure differences at the frequencies of 125 - 2000 Hz and 6300 - 8000 Hz, but the earmuff and ear canal devices were not. Noise attenuation improvement due to training over the fitting without training ranged from 7.2 to 14.6 dB, depending on the frequency and the earplug. The foam plug had the largest low frequency (1000 Hz and below) training benefit for improved protection.

2. Although, in general, achieved spectral HPD attenuation did not significantly change over a 3-week usage period, slight attenuation loss (an average of 2.8 dB across the period) was observed in the subject-fit condition, whereas slight attenuation gain was realized in the trained-fit condition. Over the same 3-week period, the foam plug showed improved attenuation due to training after 2 weeks. However, the premolded UltraFit did not exhibit any attenuation change over the period under trained-fit.

3. For all devices, attenuation standard deviations (SDs) achieved under the trained-fit condition were considerably smaller than those obtained under subject-fit.

4. The manufacturers' labeled noise reduction ratings (NRRs) substantially overestimate the actual field NRRs. When field subject-fit (considered the most realistic field fitting condition) was employed, the discrepancies ranged from 9 to 36 dB, depending on the HPD and the SD corrections used in NRR calculation. Also, overestimation by the manufacturers' spectral attenuation data is noticeable.

5. The perceived comfort afforded by the foam plug was significantly higher under subject-fit than under trained-fit. However, other devices, particularly the muff and canal cap devices, were insensitive to the fitting effect.

6. Based on the overall experience ratings, the field subjects judged the premolded earplug as the most acceptable and best-fit HPD, whereas the canal cap device was rated as the least acceptable and least attractive HPD.

7. Laboratory versus field contrasts revealed that the laboratory simulation protocol did not yield reliably accurate predictions of HPD performance under actual field conditions for certain HPDs; this occurred for both earplugs in attenuation estimation, and for the premolded earplug and the earmuff in comfort prediction. However, the earmuff laboratory results yielded a better prediction of field attenuation than did the other devices, as was the case for the foam earplug in estimating field comfort.

8. To verify the levels of protection that a worker is actually receiving, the true NRR can be estimated on a reasonably accurate basis from single-frequency attenuation measurements on the individual. Based on the findings from this study, the frequencies of 500 or 1000 Hz are recommended. Predictions were

sufficiently accurate for all devices (particularly for the practical attenuation range of 10 - 30 dB) to enable an estimate of the broadband protection obtained by the worker, based solely on a quick, single-frequency audiometric measurement.

Implications and Recommendations

The implications from the current research and recommendations for future study are as follows:

1. Since the results of this study emphasize the significance of the training effect in the industrial workplace, careful HPD selection and user training for better HPD fitting should be provided to workers to help them achieve adequate protection. When developing fitting instructions, which are often designed to achieve an optimum noise seal, attention should be provided to comfort as well as attenuation considerations. Motivational strategies should also be implemented along with the training. Several behavioral intervention strategies have been suggested to motivate HPD use in the workplace. Among them are audiometric information feedback (e.g., Zohar, Cohen, and Azar, 1980) and education (e.g., Stapleton and Royster, 1985). Other strategies, which may be adapted from other applications to help increase HPD use in the field, include using reminders (e.g., Thyer and Geller, 1987), pre-behavior incentives (e.g., Geller and Hahn, 1984), and post-behavior rewards (e.g., Zohar, 1980). It is emphasized that management should include training and motivational strategies as a part of a good hearing conservation program.

2. Since the field data provided attenuation far below the levels reported by the manufacturers, as well as below those of the post-task laboratory results, a realistic derating scheme appears necessary to help avoid overestimation of field protection levels. At this stage it is not possible to devise a precise, global derating scheme which would be appropriate for all devices. However, such a derating scheme should <u>not</u> be constant for all types of devices as suggested in the 50% scheme from OSHA (1983b) and the 10 dB reduction scheme from Berger (1983, 1986a). Because earmuff laboratory data, based on this study's results, yield better predictions of field performance than do the earplug data, it would appear that the derating percentage should be smaller for earmuffs than earplugs.

3. Although it may be difficult to devise a generic, realistic laboratory protocol to accurately estimate field HPD performance, several field influences on HPD performance warrant further investigation under controlled laboratory conditions. Such factors include environmental effects (e.g., humidity and temperature), prior experience with HPDs, and HPD adjustment/reapplication. In this way, more realistic laboratory test protocols, which closely reflect field conditions, may be developed. Currently, an American National Standards working group (ANSI S12/WG11) has devised several alternative test procedures and is evaluating their validity (Berger, 1990). When such protocols are fully developed and implemented in an HPD test standard, the need for applying an HPD-specific derating scheme to the resultant data is still quite likely, based on the findings of this study.

4. A more extensive field study needs to be conducted to provide more accurate device-specific information, including evaluation of the field performance of earmuffs and earplugs worn in combination in very loud environments. Additionally, it is suggested that a reliable and easily implemented universal field technique to verify workers' achieved attenuation with all types of HPDs be developed and validated. For example, estimation of overall field HPD noise protection can be reliably accomplished using only single-frequency (e.g., 500 and 1000 Hz) attenuation measurements, as investigated in this study. Pure-tone industrial audiometers may prove useful for that purpose, eliminating more expensive test equipment, though this needs further investigation. If such a technique were readily available to the industrial audiologist or safety professional, reasonably safe field protection levels could be easily and inexpensively established and verified for each occluded worker. In this way, the need to rely on the optimal, laboratory-based manufacturers' attenuation ratings would be alleviated.

5. Since no widely-accepted standards for testing HPD comfort are presently available, comfort specifications are not provided by HPD manufacturers, other than to make anecdotal comfort claims. Therefore, it is suggested that a standard set of rating procedures be developed to yield reliable comfort estimates so that a representative single number, perhaps akin to the comfort index herein, could then be included along with labeled attenuation ratings.

6. Finally, anthropometric data for the outer ear, excluding ear canal sizes, are currently available (Alexander and Laubach, 1968) and should be used for earmuff design. However, to the author's knowledge, no tabled anthropometric data for

ear canal sizes exist. Thus, it is recommended that population data on ear canal sizes be obtained using a standardized procedure, perhaps in conjunction with HPD attenuation and/or comfort testing. Each test laboratory could report these data on a regular basis to a central data bank. In this manner, a large set of anthropometric data, useful to earplug design and sizing, can be collected, updated, and maintained with relatively small effort.

It is hoped that the continuing efforts of this type of human factors research will help HPD designers and hearing conservationists understand problems associated with HPD effectiveness in the field, consequently improving the protection of industrial workers from hazardous occupational noise exposure and noise-induced hearing loss.

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Appendix A. OVERALL DESCRIPTION OF THE STUDY

OVERALL DESCRIPTION OF THE STUDY

Your company (Virginia Tech) is participating in a research study to assess how hearing protectors function under workplace conditions. Because you normally wear hearing protectors on your job, it would be very helpful to the Virginia Tech research team if you would volunteer to participate in the study. A brief description of this study follows.

You will be asked to attend eight sessions of approximately one hour each over a two-month period. For each session you will be transported to and from Whittemore Hall on the Virginia Tech campus by a member of the research team. An audiometric screening test and pre-experimental questionnaire (to determine if you qualify for the experiment) and an informed consent document (to obtain your consent to participate) will be given to you during the first session. If you qualify and decide to participate you will be given new hearing protectors and told to wear them, according to a specified fitting procedure, while on the job for a one-month period. Then, at three random times during the month, you will be greeted by the experimenter and taken to the lab for a brief hearing test while you are still wearing your hearing protectors as found on the job. Each of these experimental sessions will last about one hour. During each experimental session, you will undergo two occluded (with a hearing protector) and two unoccluded (without a hearing protector) hearing tests using very quiet tones. You will also perform hearing protector comfort ratings using a scale provided during each session. More detailed instructions on the specific hearing tests and hearing protector comfort ratings will be given to you at the time of their occurrence. During the second month, you will again have four sessions which will be identical to those of the first month, but you will be shown a different procedure for fitting your protectors. *You will be paid $50 at the conclusion of the final experimental session for your participation.*

This study poses no additional risks to those which are possibly inherent under your normal work conditions and at no time during the experimental sessions will your hearing be exposed to loud noises. All experimental sessions will consist of simple hearing tests using standard audiometric procedures.

Should you agree to participate, the following three things are important to remember:

1) You should always fit the hearing protectors as instructed by the research team.

2) You should consistently wear your hearing protectors while at work, particularly when there is any high-level noise present. It is imperative that you make a strong, personal effort to use your hearing protection during the course of the study, and thereafter as well, to reduce the possibility of permanent noise-induced hearing loss.

3) When the experimenter arrives at your work, it is very important that you do not readjust your hearing protectors or touch your ears prior to your hearing tests.

If at any time during the study you have any questions regarding the experiment or need a new set of hearing protectors, you should call one of the following members of the research team immediately:

Mr. Min-Yong Park	Office: 231-9086	Home: 552-3546
Dr. John G. Casali	Office: 231-5073	

Also, your permission is needed for the research team to review your hearing test results that are on file with the Health and Safety Office at Virginia Tech. These audiograms will be checked for the sole purpose of determining if your hearing ability will qualify for this study. The test results will be reviewed under the supervision of Ms. Barbara Harich of the Health and Safety Office and your results will be kept completely confidential.

Permission granted to review prior hearing test results:

____
signature

____
date signed

____
printed name

Appendix B. PRE-EXPERIMENTAL QUESTIONNAIRE

PRE-EXPERIMENTAL QUESTIONNAIRE

Initials _______ Sex ______ Age _____ Company Name ___________________

Work Phone __________________ Home Phone ______________________

1. What *type of hearing protector* are you currently using in your job? (Give a model or brand name, if possible.)

Type/Model	*Manufacturer*
________________________________	________________________
(e.g., foam earplug, rubber earplug, etc.)	(e.g., E-A-R, Bilsom, etc.)

2. Approximately how long have you used this particular hearing protector? (Please specify the number of year and months.)

   ____

3. Have you used other type(s) of hearing protector(s) before?

   Yes _____ No _____

   If yes, give the type(s) /model(s) and the approximate time period that you used them.

Type(s)/Model(s)	*Term Used*
__________________________________	_________________________
__________________________________	_________________________
__________________________________	_________________________

4. To the best of your knowledge, do you currently have any of the following related to your hearing? (Check all that are appropriate.)

   Ringing in the ears _____
   Excessive ear wax _____
   Medical diagnosis of a current hearing disorder _____
   Allergies affecting your hearing _____
   Bruises or cuts on or around the ear _____
   Other hearing related problems (please specify) _____

   ____

Appendix C. PARTICIPANT'S INFORMED CONSENT DOCUMENT

SUBJECT'S INFORMED CONSENT

HEARING PROTECTION DEVICE STUDY

Your right and left ear hearing will first 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. **Just as soon as you hear a tone, press the button on the hand switch and hold it down whenever you can hear the tone and release it when you do not hear the tone.** The tones will be very faint and you will have to listen very carefully to hear them.

No loud, harmful sounds, or other danger 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. An intercom system will be provided for your communication with the experimenter by simply talking. (There are no buttons to push.) A closed-circuit TV system will also be used to monitor the interior of the chamber, but a videotape recording will not be made.

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 performance of the hearing protector.

As a participant in this experiment, you have certain rights, as stated below. This sheet is intended 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 (four 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.**

SUBJECT'S INFORMED CONSENT (continued)

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 the 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: ______________________________

Address: ______________________________

____

____

I, the subject, do, do not (circle one) wish to receive a summary of the research results. (If the summary is desired, include address, four months, hence below)

Address: ______________________________

____

____

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.

SUBJECT'S INFORMED CONSENT (continued)

The research team for this experiment consists of Mr. Min-Yong Park, a graduate student in the IEOR Department 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

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

Chairman, University Human Subjects Committee
301 Buruss Hall
VPI&SU
Blacksburg, VA 24061
(703) 231-5283

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

Appendix D. INSTRUCTIONS FOR AUDIOMETRIC SCREENING TEST

INSTRUCTIONS FOR AUDIOMETRIC SCREENING TEST

During this session your hearing will be tested using very quiet tones. A pair of earphones will be placed over your ears. Once the earphones are in place, **please do not adjust or touch them**. If the earphones move or slip, or feel uncomfortable, please inform the experimenter. Your left and right ears will be individually tested using several different tones.

The test tone will be "beeping" or "pulsating." As soon as you first hear the tone, press the response button and hold it down until you no longer hear the tone. Then, prepare to listen for the next beeping tone. Listen carefully at all times because you will just barely be able to hear the beeps if you are doing the test correctly. Remember to push the button when you think you first hear the beeping tone and release it when you no longer hear the tone. A two-way intercom system is provided for your communication with the experimenter. If you have any problem during the tests, please speak and the experimenter will be able to hear you.

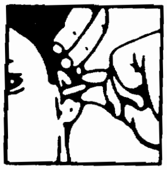
Appendix E. MANUFACTURER'S PACKAGE INSTRUCTIONS FOR EACH HPD

E-A-R Foam Plug

IMPORTANT
Easy-to-Follow Instructions

1
With clean hands hold earplug between index finger and thumb

2
Slowly roll and compress earplug into a very thin, crease-free cylinder



3
While compressed, insert earplugs well into ear canal. Fitting is easier if outer ear is pulled outwards and upwards during insertion

4
With fingertip hold earplug in place until it begins to expand and block noise.

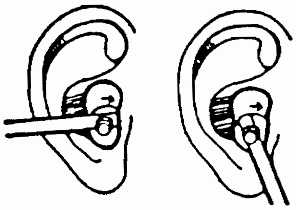
UltraFit Flanged Plug

HOW TO USE
Grasp the plug by the stem and insert into the canal until the ear feels sealed. Adjust the plug for greatest noise reduction. Fitting is easier if the ear is pulled outwards and upwards during insertion.

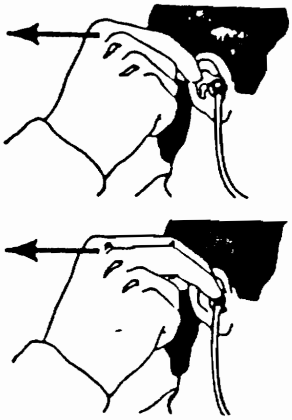
CLEANING
Plugs should be routinely washed with mild soap and warm water.

Willson Sound-Ban Canal Cap

1. Turn headband to desired position, then adjust pods so arrow is on top pointing forward when positioned in ear.



2. Place pods in ear, grasp pods (not cap nut) and work them forward and into ear until ear canal is completely covered.
3. Then, grasp ears and pull out and back while applying *slight* inward pressure on the pods.



Bilsom UF-1 Muff

Fitting: For best seal, remove as much hair as possible from under ear cushions. Pencils and other objects should not be stored behind the ear. You can adjust height of cups by sliding knob up or down. Adjust band for minimum space between head and band. Thanks to flexible headband attachment, muffs are self-aligning.

Caution Do not attempt to alter shape of headband.

Appendix F. QUESTIONNAIRE FOR ESTIMATING DAILY HPD WEARING TIME

Name ____________________

Please estimate about how long you wore your hearing protector each day. (Put a mark on the line below to indicate how much time.)

Estimated Hours Worn Each Day

Date

_______ 0 1 2 3 4 5 6 7 8

Hours

_______ 0 1 2 3 4 5 6 7 8

Hours

_______ 0 1 2 3 4 5 6 7 8

Hours

_______ 0 1 2 3 4 5 6 7 8

Hours

_______ 0 1 2 3 4 5 6 7 8

Appendix G. ESTIMATED AVERAGE DAILY HPD WEARING TIME

Estimated Daily Wearing Time[1] (in hour) for Each HPD (by Fitting Procedure and Week)

HPD[2]:	E		U		B		W	
Fitting Procedure[3]:	S-F	T-F	S-F	T-F	S-F	T-F	S-F	T-F
Week[4]								
W1	5.7	5.5	5.3	4.3	2.9	2.8	4.6	3.8
W2	5.8	6.2	5.0	5.1	2.8	3.5	3.8	3.6
W3	6.0	5.7	5.5	4.6	3.2	3.3	3.6	3.5
Mean[5]	5.8	5.8	5.3	4.7	3.0	3.2	4.0	3.6
HPD[2]:	E		U		B		W	
Grand Mean[6]	5.8		5.0		3.1		3.8	

[1] Based on a 8-hour daily work-shift.

[2] E = E-A-R foam plug; U = UltraFit flanged plug; B = Bilsom muff; W = Willson canal cap.

[3] S-F = Subject-Fit; T-F = Trained-Fit.

[4] W1 = Week 1; W2 = Week 2; W3 = Week 3.

[5] For each HPD under each fitting procedure (collapsed across 3 weeks).

[6] For each HPD (collapsed across 2 fitting procedures and 3 weeks).

Appendix H. INSTRUCTIONS FOR FITTING THE HPD (SUBJECT-FIT)

INSTRUCTIONS FOR FITTING THE HEARING PROTECTOR (SUBJECT-FIT)

You will be wearing a hearing protector, supplied by the research team, in your workplace. You must put on the hearing protector by yourself using only the hearing protector manufacturer's package instructions concerning proper fit. The experimenter cannot provide any verbal or physical assistance for fitting the protector and cannot answer questions concerning its placement. Carefully read the package instructions and apply the hearing protector exactly as the directions indicate.

After wearing the given hearing protector for a while on the job, you will then be pulled (unannounced) from your work site three times over a three-week period for hearing tests.

Once you are pulled from your work site, it is imperative that you not adjust or touch your hearing protector until the end of the experimental session.

Appendix I. INSTRUCTIONS FOR FITTING THE HPD (TRAINED-FIT)

INSTRUCTIONS FOR FITTING THE HEARING PROTECTOR (TRAINED-FIT)

You will be wearing a hearing protector, supplied by the research team, in your workplace. You will learn to properly fit the hearing protector with the experimenter's help; however, you will be required to fit the protector by yourself each day at work. It is very important that you learn to fit the protector so that it provides an effective noise-blocking seal. To do this, you must carefully read and understand the manufacturer's package instructions and then pay close attention as the experimenter assists you in fitting the protector in accordance with those instructions. You may re-read the instructions as many times as necessary and ask any questions of the experimenter while learning to fit the protector. *Remember the quality of the fit is important; it should provide for an effective noise-blocking seal while affording a reasonable degree of comfort* (that is, it is comfortable enough that you could wear it for your work shift while engaged in normal work activities).

After you are convinced that you can obtain the best fit possible, you will return to your work environment then fit and wear the assigned protector, as you practiced, for a while on the job. You will then be pulled (unannounced) from your work site three times over a three-week period for hearing tests. *Once you are pulled from your work site, it is imperative that you not adjust or touch your hearing protector until the end of the experimental session.*

Appendix J. HAND-HELD SIGN USED FOR SUBJECT PICK-UP

IT IS TIME FOR YOUR HEARING TEST.

PLEASE PREPARE NOW TO LEAVE YOUR WORKPLACE AND GO WITH THE EXPERIMENTER.

PLEASE DO NOT TOUCH OR ADJUST YOUR HEARING PROTECTOR OR TOUCH YOUR EARS!!!

THANK YOU FOR YOUR COOPERATION.

Appendix J. HAND-HELD SIGN USED FOR SUBJECT PICK-UP

Appendix K. INSTRUCTIONS FOR THE HPD ATTENUATION TESTS

SUBJECT INSTRUCTIONS FOR THE HEARING PROTECTION DEVICE ATTENUATION TESTS

During this experimental session your hearing will be tested several times in two conditions: 1) while you are wearing a hearing protector (occluded) and 2) without the hearing protector in place (unoccluded). You will be listening for a series of quiet "beeping" or "pulsating" sounds which will be presented through the loudspeakers at several different "pitches," starting with a low bass pitch, progressing to a high treble pitch, and then ending with a low bass pitch. Just as soon as you hear any beeping sound, press the hand-held button and hold it down until you can no longer hear the beeping sound. Then, release the button and listen for the beeping sound again. When you hear the beeping sound again, press the button down again and repeat the process. Listen carefully at all times because you will just barely be able to hear the beeping sound if you are doing the test right.

A two-way intercom system will be provided for your communication with the experimenter. If you have any problem during the tests, please speak to the experimenter using the intercom system. The experimenter will also tell you the necessary messages throughout this experimental session.

Several important points you should keep in mind during the tests include:

1) Once the hearing protector has been fitted, do not touch or in any way adjust it.

2) You should remain seated with an upright posture, facing straight ahead and listening carefully for the beeping sounds at all times. Try to keep your nose close to, but not touching, the pendulum during the tests.

3) Remember to press the button when you first hear the beeping sound and keep it pressed until you no longer hear it. Whenever you do not hear a beeping sound, the button should be released and left released until you hear the sound again.

Appendix L. INSTRUCTIONS FOR HPD RATING SCALES

INSTRUCTIONS FOR HEARING PROTECTION DEVICE RATING SCALES

Throughout this experimental session you will be wearing a hearing protector designed for protection of the ears in noisy industrial environments. At several times during this session you will be asked to judge (or give your impressions concerning) the hearing protector using a series of descriptive rating scales. While rating the hearing protector, plese make your judgements on the basis of how the hearing protector feels TO YOU, at the point in time that you are providing the ratings. You will aways be making your ratings while wearing the hearing protector.

Here is a an example of how to use the rating scales:

If your impressions about how the hearing protector feels are VERY CLOSELY RELATED to one end of the scale, you should place your check-mark as follows:

LIGHT _______:_______:_______:_______:_______:_______:_______ HEAVY

or

LIGHT _______:_______:_______:_______:_______:_______:_______ HEAVY

If your impressions about how the hearing protector feels are QUITE CLOSELY RELATED to one end of the scale (but not extremely), you should place your check-mark as follows:

LIGHT _______:_______:_______:_______:_______:_______:_______ HEAVY

or

LIGHT _______:_______:_______:_______:_______:_______:_______ HEAVY

If your impressions about how the hearing protector feels while wearing it are ONLY SLIGHTLY RELATED to one end of the scale (but are not really neutral), then you should check as follows:

LIGHT _______:_______:___X___:_______:_______:_______:_______ HEAVY

or

LIGHT _______:_______:_______:_______:___X___:_______:_______ HEAVY

The direction toward which you check, of course, depends upon which of the two ends of the scale seem most characteristic of the hearing protector you are wearing, as they feel to you at that point in time.

If your impressions about how the hearing protector feels while wearing it are NEUTRAL between the ends of the scale, or if you consider the scale to be COMPLETELY IRRELEVANT, then you should place your check-mark in the middle space as follows:

LIGHT _______:_______:_______:___X___:_______:_______:_______ HEAVY

Note that the LIGHT/HEAVY scale item is just one example of those that you will be given. There are actually many different scales on which you will provide your ratings.

It is very important that you read the descriptive word(s) at both ends of each scale item and consider their meaning carefully before making your judgement. There is no left-to-right or bad-to-good pattern across all of the ratings scales, so you must carefully read each scale descriptor. Furthermore, each scale should be considered and rated separately and independently from each other scale.

IMPORTANT

1. Place your check-marks (or X-marks) IN THE MIDDLE OF SPACES, not on the boundaries:

This **Not This**

LIGHT _______:__X___:_______:_______:______X______:_______ HEAVY

2. Be sure to check every scale -- DO NOT OMIT ANY SCALES.
3. Never put more than one check-mark on a single scale.
4. **IMPORTANT:** Do not look back and forth through the rating scales.

   MAKE EACH SCALE ITEM A SEPARATE AND INDEPENDENT JUDGEMENT. READ EACH SCALE CAREFULLY.
5. Remember, it is your IMMEDIATE, ACCURATE FEELINGS about the hearing protector that are needed. Please do not be careless, because your ACTUAL and HONEST FEELINGS are necessary.

Appendix M. BIPOLAR COMFORT RATING SCALES

BIPOLAR COMFORT RATING SCALES AND ASSOCIATED INSTRUCTIONS

While you are wearing the hearing protector, rate it on the following descritpive scales. Please do not touch or adjust your hearing protector during this phase of the experiment. Carefully read the adjectives at the ends of each scale before you rate. Be sure to make your ratings based on how the hearing protector feels to you right now, as you are wearing it at this point in time. Give your immediate feelings about the hearing protector and try to make your rating on each descriptive scale independent of the other scales which are presented on the following page. Complete the scales in the order in which they are presented, without looking back and forth through the items.

HOW DOES THE HEARING PROTECTOR FEEL NOW?

Painless	_______:_______:_______:_______:_______:_______:_______	Painful
Uncomfortable	_______:_______:_______:_______:_______:_______:_______	Comfortable
No Uncomfortable Pressure	_______:_______:_______:_______:_______:_______:_______	Uncomfortable Pressure
Intolerable	_______:_______:_______:_______:_______:_______:_______	Tolerable
Tight	_______:_______:_______:_______:_______:_______:_______	Loose
Not Bothersome	_______:_______:_______:_______:_______:_______:_______	Bothersome
Heavy	_______:_______:_______:_______:_______:_______:_______	Light
Cumbersome	_______:_______:_______:_______:_______:_______:_______	Not Cumbersome
Soft	_______:_______:_______:_______:_______:_______:_______	Hard
Cold	_______:_______:_______:_______:_______:_______:_______	Hot
Smooth	_______:_______:_______:_______:_______:_______:_______	Rough
Feeling of Complete Isolation	_______:_______:_______:_______:_______:_______:_______	No Feeling of Complete Isolation
Ear Open	_______:_______:_______:_______:_______:_______:_______	Ear Blocked
Ear Empty	_______:_______:_______:_______:_______:_______:_______	Ear Full

Appendix N. BIPOLAR CONVENIENCE RATING SCALES

BIPOLAR CONVENIENCE RATING SCALES AND ASSOCIATED INSTRUCTIONS

Considering your overall experience with the hearing protector, rate it on the following descriptive scales. Carefully read the adjectives at the ends of each scale before you rate. Be sure to make your ratings based on your impressions of, and experience with the hearing protector. Try to make your rating on each descriptive scale independent of the other scales which are presented on the following page. Complete the scales in the order in which they are presented, without looking back and forth through the items.

WHAT IS YOUR OVERALL IMPRESSION OF THE HEARING PROTECTOR?

Easy to Apply _______:_______:_______:_______:_______:_______:_______ Difficult to Apply

Unacceptable _______:_______:_______:_______:_______:_______:_______ Acceptable

Good Fit _______:_______:_______:_______:_______:_______:_______ Poor Fit

Stable _______:_______:_______:_______:_______:_______:_______ Unstable

Unattractive _______:_______:_______:_______:_______:_______:_______ Attractive

Simple _______:_______:_______:_______:_______:_______:_______ Complicated

Easily Loosens _______:_______:_______:_______:_______:_______:_______ Doesn't Loosen

Inhibits Head Movement _______:_______:_______:_______:_______:_______:_______ Doesn't Inhibit Head Movement

Appendix O. COMPARISON STATISTICS FOR OVERALL LABORATORY VS. FIELD ATTENUATION

Appendix O - 1

Summary Statistics for *t*-tests Attenuation Comparisons[1] with Overall Laboratory Data (for the E-A-R Foam Plug)

	Paired *t* Statistics[2]		Two-sample *t* Statistics[3]			
Test Freq. (Hz)	FT-FS	LT-LS	LS-FS	LS-FT	LT-FT	LT-FS
125	6.18**	6.02**	2.20*	1.84	2.18*	5.17**
250	5.86**	7.64**	2.11*	2.21*	2.28*	5.07**
500	5.87**	8.91**	2.21*	2.66*	2.83*	4.91**
1000	5.84**	10.95**	2.15*	2.26*	3.17**	5.44**
2000	2.49*	7.03**	1.45	0.56	1.07	2.17*
3150	2.30*	5.26**	1.81	0.0	3.00**	2.81*
4000	2.47*	3.85**	2.79*	-1.66	4.02**	3.84**
6300	2.72*	2.41*	3.51**	-1.48	2.36*	4.13**
8000	2.91*	2.45*	3.26**	-1.15	3.29**	4.94**

[1] FT = Field Trained-Fit; FS = Field Subject-Fit

LT = Laboratory Trained-Fit; LS = Laboratory Subject-Fit

[2] $t = \dfrac{\bar{D}}{\sqrt{\dfrac{S_D^2}{n}}} \sim t_\alpha(n-1)$, where $n = 10$; $t_{0.05}(9) = 2.26$; $t_{0.01}(9) = 3.25$;

D = difference of the paired means; and S_D^2 = variance of D

[3] $t = \dfrac{d}{S_p\sqrt{\dfrac{1}{n_1}+\dfrac{1}{n_2}}} \sim t_\alpha(n_1+n_2-2)$, where $n_1 = n_2 = 10$;

$t_{0.05}(18) = 2.10$; $t_{0.01}(18) = 2.88$;

d = difference of two sample means; and

$S_p^2 = \dfrac{(n_1-1)S_1^2+(n_2-1)S_2^2}{n_1+n_2-2}$, S_i^2 = variance of sample data i ($i = 1, 2$)

* Statistically significant at $p < 0.05$.

** Statistically significant at $p < 0.01$.

Appendix O - 2

Summary Statistics for *t*-tests Attenuation Comparisons[1] with Overall Laboratory Data (for the UltraFit Plug)

	Paired *t* Statistics[2]		Two-sample *t* Statistics[3]			
Test Freq. (Hz)	FT-FS	LT-LS	LS-FS	LS-FT	LT-FT	LT-FS
125	5.07**	3.72**	3.15*	-0.34	2.19*	4.69**
250	4.81**	3.03*	2.79*	-0.53	2.22*	4.41**
500	4.21**	3.36**	2.72*	-0.85	2.67*	4.30**
1000	3.43**	2.89*	2.16*	-0.04	2.83*	3.33**
2000	2.98*	2.82*	3.33**	-1.83	6.22**	5.17**
3150	3.21*	2.44*	3.14**	-1.84	4.50**	5.09**
4000	3.55**	1.85	3.26**	-1.35	3.02**	4.84**
6300	5.46**	0.93	4.80**	-2.17*	3.60**	6.02**
8000	5.02**	2.69*	4.49**	-1.32	4.10**	7.72**

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[1] FT = Field Trained-Fit; FS = Field Subject-Fit

LT = Laboratory Trained-Fit; LS = Laboratory Subject-Fit

[2] $$t = \frac{\bar{D}}{\sqrt{\frac{S_D^2}{n}}} \sim t_\alpha(n-1), \text{ where } n = 10;\ t_{0.05}(9) = 2.26;\ t_{0.01}(9) = 3.25;$$

D = difference of the paired means; and S_D^2 = variance of D

[3] $$t = \frac{d}{S_p\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}} \sim t_\alpha(n_1+n_2-2), \text{ where } n_1 = n_2 = 10;$$

$t_{0.05}(18) = 2.10;\ t_{0.01}(18) = 2.88;$

d = difference of two sample means; and

$$S_p^2 = \frac{(n_1-1)S_1^2 + (n_2-1)S_2^2}{n_1+n_2-2},\quad S_i^2 = \text{variance of sample data } i\ (i = 1, 2)$$

* Statistically significant at $p < 0.05$.

** Statistically significant at $p < 0.01$.

Appendix O - 3

Summary Statistics for *t*-tests Attenuation Comparisons[1] with Overall Laboratory Data (for the Bilsom UF-1 Muff)

	Paired *t* Statistics[2]		Two-sample *t* Statistics[3]			
Test Freq. (Hz)	FT-FS	LT-LS	LS-FS	LS-FT	LT-FT	LT-FS
125	1.15	0.94	0.64	0.20	0.31	1.01
250	1.58	1.57	0.82	0.51	0.36	1.34
500	1.63	2.04	0.22	1.18	0.11	1.03
1000	0.56	2.11	0.15	0.21	0.98	0.91
2000	1.68	1.43	0.45	0.60	0.26	1.46
3150	2.11	2.09	0.34	0.78	1.24	2.73*
4000	2.07	1.59	0.23	0.63	0.61	1.65
6300	0.47	0.36	1.12	-0.97	1.92	1.88
8000	0.79	1.15	0.48	-0.26	1.35	1.48

[1] FT = Field Trained-Fit; FS = Field Subject-Fit

LT = Laboratory Trained-Fit; LS = Laboratory Subject-Fit

[2] $t = \dfrac{\overline{D}}{\sqrt{\dfrac{S_D^2}{n}}} \sim t_\alpha(n-1)$, where $n = 10$; $t_{0.05}(9) = 2.26$; $t_{0.01}(9) = 3.25$;

D = difference of the paired means; and S_D^2 = variance of D

[3] $t = \dfrac{d}{S_p\sqrt{\dfrac{1}{n_1}+\dfrac{1}{n_2}}} \sim t_\alpha(n_1+n_2-2)$, where $n_1 = n_2 = 10$;

$t_{0.05}(18) = 2.10$; $t_{0.01}(18) = 2.88$;

d = difference of two sample means; and

$S_p^2 = \dfrac{(n_1-1)S_1^2+(n_2-1)S_2^2}{n_1+n_2-2}$, S_i^2 = variance of sample data i ($i = 1, 2$)

* Statistically significant at $p < 0.05$.

** Statistically significant at $p < 0.01$.

Appendix P. COMPARISON STATISTICS FOR PRE-TASK LABORATORY VS. FIELD ATTENUATION

Appendix P - 1

Summary Statistics for *t*-tests Attenuation Comparisons[1] with the Pre-task Laboratory Data (for the E-A-R Foam Plug)

	Paired *t* Statistics[2]		Two-sample *t* Statistics[3]			
Test Freq. (Hz)	FT-FS	LT-LS	LS-FS	LS-FT	LT-FT	LT-FS
125	6.18**	6.36**	4.57**	-3.88**	4.23**	10.10**
250	5.86**	7.97**	5.07**	-4.39**	4.41**	10.48**
500	5.87**	8.78**	4.14**	-5.68**	3.91**	10.78**
1000	5.84**	10.02**	5.21**	-4.89**	6.09**	11.82**
2000	2.49*	5.38**	3.33**	-1.23	1.74	4.80**
3150	2.30*	4.95**	4.44**	0.51	6.67**	7.07**
4000	2.47*	3.94**	6.44**	3.13**	7.72**	9.00**
6300	2.72*	2.33*	8.59**	3.76**	5.50**	9.75**
8000	2.91*	2.41*	6.86**	2.46*	6.89**	11.11**

[1] FT = Field Trained-Fit; FS = Field Subject-Fit
LT = Laboratory Trained-Fit; LS = Laboratory Subject-Fit

[2] $t = \dfrac{\bar{D}}{\sqrt{\dfrac{S_D^2}{n}}} \sim t_\alpha(n-1)$, where $n = 10$; $t_{0.05}(9) = 2.26$; $t_{0.01}(9) = 3.25$;
D = difference of the paired means; and S_D^2 = variance of D

[3] $t = \dfrac{d}{S_p\sqrt{\dfrac{1}{n_1} + \dfrac{1}{n_2}}} \sim t_\alpha(n_1 + n_2 - 2)$, where $n_1 = n_2 = 10$;
$t_{0.05}(18) = 2.10$; $t_{0.01}(18) = 2.88$;
d = difference of two sample means; and
$S_p^2 = \dfrac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}$, S_i^2 = variance of sample data i ($i = 1, 2$)

* Statistically significant at $p < 0.05$.

** Statistically significant at $p < 0.01$.

Appendix P - 2

Summary Statistics for *t*-tests Attenuation Comparisons[1] with the Pre-task Laboratory Data (for the UltraFit Plug)

	Paired *t* Statistics[2]		Two-sample *t* Statistics[3]			
Test Freq. (Hz)	FT-FS	LT-LS	LS-FS	LS-FT	LT-FT	LT-FS
125	5.07**	3.30**	7.60**	2.91**	4.49**	8.94**
250	4.81**	5.04**	5.32**	1.74	4.05**	7.76**
500	4.21**	4.26**	5.08**	2.00	4.57*	7.72**
1000	3.43**	5.05**	4.46**	1.23	3.36**	6.38**
2000	2.98*	2.39*	8.33**	5.05**	10.54**	12.08**
3150	3.21*	2.13	7.12**	4.44**	6.81**	9.22**
4000	3.55**	1.80	6.83**	3.36**	5.75**	9.40**
6300	5.46**	0.43	9.16**	4.37**	6.14**	11.48**
8000	5.02**	2.87*	8.51**	2.88**	8.80**	16.52**

[1] FT = Field Trained-Fit; FS = Field Subject-Fit

LT = Laboratory Trained-Fit; LS = Laboratory Subject-Fit

[2] $t = \dfrac{\overline{D}}{\sqrt{\dfrac{S_D^2}{n}}} \sim t_\alpha(n-1)$, where $n = 10$; $t_{0.05}(9) = 2.26$; $t_{0.01}(9) = 3.25$;

D = difference of the paired means; and S_D^2 = variance of D

[3] $t = \dfrac{d}{S_p\sqrt{\dfrac{1}{n_1}+\dfrac{1}{n_2}}} \sim t_\alpha(n_1+n_2-2)$, where $n_1 = n_2 = 10$;

$t_{0.05}(18) = 2.10$; $t_{0.01}(18) = 2.88$;

d = difference of two sample means; and

$S_p^2 = \dfrac{(n_1-1)S_1^2+(n_2-1)S_2^2}{n_1+n_2-2}$, S_i^2 = variance of sample data i ($i = 1, 2$)

* Statistically significant at $p < 0.05$.

** Statistically significant at $p < 0.01$.

Appendix P - 3

Summary Statistics for *t*-tests Attenuation Comparisons[1] with the Pre-task Laboratory Data (for the Bilsom Muff)

	Paired *t* Statistics[2]		Two-sample *t* Statistics[3]			
Test Freq. (Hz)	FT-FS	LT-LS	LS-FS	LS-FT	LT-FT	LT-FS
125	1.15	1.40	2.36*	1.01	2.24*	3.29**
250	1.58	2.01	3.27**	1.10	2.56*	4.12**
500	1.63	0.71	2.18*	0.43	1.26	2.86*
1000	0.56	1.21	1.15	0.62	2.27*	2.36*
2000	1.68	0.31	2.17*	0.26	0.62	2.77*
3150	2.11	1.76	0.96	-0.82	1.37	3.70**
4000	2.07	2.24	1.19	-0.42	2.04	4.20**
6300	0.47	-1.24	3.13**	2.82*	2.54*	2.90**
8000	0.79	0.93	1.53	1.16	3.00**	3.36**

[1] FT = Field Trained-Fit; FS = Field Subject-Fit

LT = Laboratory Trained-Fit; LS = Laboratory Subject-Fit

[2] $t = \dfrac{\bar{D}}{\sqrt{\dfrac{S_D^2}{n}}} \sim t_\alpha(n-1)$, where $n = 10$; $t_{0.05}(9) = 2.26$; $t_{0.01}(9) = 3.25$;

D = difference of the paired means; and S_D^2 = variance of D

[3] $t = \dfrac{d}{S_p\sqrt{\dfrac{1}{n_1} + \dfrac{1}{n_2}}} \sim t_\alpha(n_1 + n_2 - 2)$, where $n_1 = n_2 = 10$;

$t_{0.05}(18) = 2.10$; $t_{0.01}(18) = 2.88$;

d = difference of two sample means; and

$S_p^2 = \dfrac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}$, S_i^2 = variance of sample data i ($i = 1, 2$)

* Statistically significant at $p < 0.05$.

** Statistically significant at $p < 0.01$.

Appendix Q. COMPARISON STATISTICS FOR POST-TASK LABORATORY VS. FIELD ATTENUATION

Appendix Q - 1

Summary Statistics for *t*-tests Attenuation Comparisons[1] with the Post-task Laboratory Data (for the E-A-R Foam Plug)

	Paired *t* Statistics[2]		Two-sample *t* Statistics[3]			
Test Freq. (Hz)	FT-FS	LT-LS	LS-FS	LS-FT	LT-FT	LT-FS
125	6.18**	7.38**	4.69**	-3.84**	3.58**	9.23**
250	5.86**	7.92**	4.46**	-5.57**	4.20**	10.51**
500	5.87**	8.49**	3.86**	-6.34**	3.67**	10.75**
1000	5.84**	8.07**	5.01**	-5.11**	6.09**	11.90**
2000	2.49*	2.47*	3.28**	-1.34	2.15*	4.97**
3150	2.30*	2.86*	3.84**	-0.60	5.71**	6.55**
4000	2.47*	2.25	6.20**	2.69*	7.22**	8.63**
6300	2.72*	1.60	7.51**	2.58*	4.66**	9.09**
8000	2.91*	1.88	5.89**	1.57	6.45**	10.90**

[1] FT = Field Trained-Fit; FS = Field Subject-Fit
LT = Laboratory Trained-Fit; LS = Laboratory Subject-Fit

[2] $t = \dfrac{\bar{D}}{\sqrt{\dfrac{S_D^2}{n}}} \sim t_\alpha(n-1)$, where $n = 10$; $t_{0.05}(9) = 2.26$; $t_{0.01}(9) = 3.25$;
D = difference of the paired means; and S_D^2 = variance of D

[3] $t = \dfrac{d}{S_p\sqrt{\dfrac{1}{n_1} + \dfrac{1}{n_2}}} \sim t_\alpha(n_1 + n_2 - 2)$, where $n_1 = n_2 = 10$;
$t_{0.05}(18) = 2.10$; $t_{0.01}(18) = 2.88$;
d = difference of two sample means; and
$S_p^2 = \dfrac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}$, S_i^2 = variance of sample data i ($i = 1, 2$)

* Statistically significant at $p < 0.05$.

** Statistically significant at $p < 0.01$.

Appendix Q - 2

Summary Statistics for *t*-tests Attenuation Comparisons[1] with the Post-task Laboratory Data (for the UltraFit Plug)

	Paired *t* Statistics[2]		Two-sample *t* Statistics[3]			
Test Freq. (Hz)	FT-FS	LT-LS	LS-FS	LS-FT	LT-FT	LT-FS
125	5.07**	3.35**	3.37**	-1.23	1.58	6.48**
250	4.81**	2.48*	3.68**	-0.15	2.74*	7.45**
500	4.21**	2.76*	4.06**	0.63	3.40**	7.02**
1000	3.43**	3.74**	3.07**	-0.97	1.55	5.27**
2000	2.98*	2.74*	4.93**	0.89	7.97**	10.06**
3150	3.21*	2.42*	4.12**	1.61	6.48**	9.12**
4000	3.55**	1.92	4.41**	1.08	3.96**	7.76**
6300	5.46**	1.39	7.49**	2.20*	5.37**	11.22**
8000	5.02**	2.64*	6.49**	1.41	7.09**	15.01**

[1] FT = Field Trained-Fit; FS = Field Subject-Fit
LT = Laboratory Trained-Fit; LS = Laboratory Subject-Fit

[2] $t = \dfrac{\bar{D}}{\sqrt{\dfrac{S_D^2}{n}}} \sim t_\alpha(n-1)$, where $n = 10$; $t_{0.05}(9) = 2.26$; $t_{0.01}(9) = 3.25$;
D = difference of the paired means; and S_D^2 = variance of D

[3] $t = \dfrac{d}{S_p\sqrt{\dfrac{1}{n_1}+\dfrac{1}{n_2}}} \sim t_\alpha(n_1+n_2-2)$, where $n_1 = n_2 = 10$;

$t_{0.05}(18) = 2.10$; $t_{0.01}(18) = 2.88$;

d = difference of two sample means; and

$S_p^2 = \dfrac{(n_1-1)S_1^2+(n_2-1)S_2^2}{n_1+n_2-2}$, S_i^2 = variance of sample data i ($i = 1, 2$)

* Statistically significant at $p < 0.05$.

** Statistically significant at $p < 0.01$.

Appendix Q - 3

Summary Statistics for *t*-tests Attenuation Comparisons[1] with the Post-task Laboratory Data (for the Bilsom Muff)

	Paired *t* Statistics[2]		Two-sample *t* Statistics[3]			
Test Freq. (Hz)	FT-FS	LT-LS	LS-FS	LS-FT	LT-FT	LT-FS
125	1.15	0.06	0.54	-0.72	-1.04	0.95
250	1.58	0.70	0.57	-1.58	-0.76	1.51
500	1.63	2.73*	-0.62	-3.05**	-0.83	1.69
1000	0.56	1.04	-0.38	-0.89	1.18	1.59
2000	1.68	1.75	-0.11	-1.49	0.87	3.32**
3150	2.11	2.43*	0	-1.42	2.80*	5.83**
4000	2.07	1.27	0	-1.19	0.61	2.99**
6300	0.47	0.99	0.88	0.54	4.05**	4.16**
8000	0.79	2.34*	0.05	-0.33	2.21*	2.66*

[1] FT = Field Trained-Fit; FS = Field Subject-Fit

LT = Laboratory Trained-Fit; LS = Laboratory Subject-Fit

[2] $t = \dfrac{\bar{D}}{\sqrt{\dfrac{S_D^2}{n}}} \sim t_\alpha(n-1)$, where $n = 10$; $t_{0.05}(9) = 2.26$; $t_{0.01}(9) = 3.25$;

D = difference of the paired means; and S_D^2 = variance of D

[3] $t = \dfrac{d}{S_p\sqrt{\dfrac{1}{n_1}+\dfrac{1}{n_2}}} \sim t_\alpha(n_1 + n_2 - 2)$, where $n_1 = n_2 = 10$;

$t_{0.05}(18) = 2.10$; $t_{0.01}(18) = 2.88$;

d = difference of two sample means; and

$S_p^2 = \dfrac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}$, S_i^2 = variance of sample data i ($i = 1, 2$)

* Statistically significant at $p < 0.05$.

** Statistically significant at $p < 0.01$.

Appendix R. COMPARISON STATISTICS FOR LABORATORY VS. FIELD COMFORT INDEX

Summary Statistics for Two-sample *t*-tests[1] Comparisons[2] (Laboratory vs. Field) of the Comfort Index Data for Each HPD

Bilsom Muff		E-A-R Foam Plug		UltraFit Plug	
FS-LS	FT-LT	FS-LS	FT-LT	FS-LS	FT-LT
2.65*	3.63**	0.77	1.73	0.21	2.33*

[1] $$t = \frac{d}{S_p\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}} \sim t_\alpha(n_1+n_2-2), \text{ where } n_1 = n_2 = 10;$$

$t_{0.05}(18) = 2.10$; $t_{0.01}(18) = 2.88$;

d = difference of two sample means; and

$$S_p^2 = \frac{(n_1-1)S_1^2+(n_2-1)S_2^2}{n_1+n_2-2}, \quad S_i^2 = \text{variance of sample data } i \ (i = 1, 2)$$

[2] FT = Field Trained-Fit; FS = Field Subject-Fit

LT = Laboratory Trained-Fit; LS = Laboratory Subject-Fit

* Statistically significant at $p < 0.05$.

** Statistically significant at $p < 0.01$.

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Mr. Min-Yong Park, born on February 21, 1955, in Kimcheon, Korea, received his B.S. and M.S. degrees in Industrial Engineering from Hanyang University (Seoul, Korea), an M.S. degree in Industrial Engineering and Management from Oklahoma State University, Stillwater, Oklahoma, and an M.S. degree in Industrial Engineering and Operations Research (human factors option) from Virginia Polytechnic Institute and State University, Blacksburg, Virginia. He is currently completing his Ph.D. degree in Industrial and Systems Engineering with concentration in human factors from Virginia Polytechnic Institute and State University.

He served as a graduate teaching assistant for numerous courses, including Manufacturing Systems Design, Engineering Economy, Systems Simulation, Quantitative Methods for Industrial Engineering, Stochastic Processes, Operations Research, and Quality Control/Industrial Statistics at Oklahoma State University. While at Virginia Tech, he has served as a graduate research assistant in the Auditory Systems Laboratory and been involved in conducting two NIH/NIOSH-funded human factors research projects on hearing protector effectiveness. He has also served as a graduate teaching assistant for the following courses: Introduction to Industrial Engineering, Design and Evaluation of Human/Machine Systems, Human Factors Research Design, Industrial/Organizational Psychology, Occupational Safety and Hazard Control, and Systems Safety Analysis. His current research interests include human-machine system design, occupational safety/hearing protection, human-computer interaction, and research methods/applied statistics. His research has been published in several refereed journals and proceedings, including Human Factors, Journal of Sound and Vibration, Applied Acoustics, The Journal of Acoustical

Society of America, *Proceedings of the Human Factors Society*, *American Industrial Hygiene Conference*, and *National Hearing Conservation Association Meeting*.

Mr. Min-Yong Park was the recipient of the 1990 Institute of Industrial Engineers Graduate Research Award National Competition (third place), the 1989-1990 College of Engineering Graduate Research Excellence Award at Virginia Tech (M.S. competition: third place), and the 1990-1991 College of Engineering Graduate Research Excellence Award at Virginia Tech (Ph.D. competition: third place). He is a student member of the Human Factors Society, Institute of Industrial Engineers, Acoustical Society of America, American Society of Safety Engineers, and American Society for Quality Control. He also holds membership in the honor societies of Phi Kappa Phi and Alpha Pi Mu.