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A Controlled Investigation of In-Field Attenuation Performance of Selected Insert, Earmuff, and Canal Cap Hearing Protectors

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A field study assessed the actual spectral noise attenuation achieved by 40 industrial workers wearing four different hearing protection devices (HPDs) while on the job. The effect of two different HPD fitting procedures (subject fit vs. trained fit) on attenuation performance over two three-week periods of protector use was determined. Subjects were retrieved from their workplaces without prior knowledge of when they were to be tested and were not permitted to readjust the fit of their HPDs. Attenuation data were then collected using psychophysical procedures testing real ear attenuation at threshold. Statistical analyses indicated that the earplugs' attenuation significantly improved when training for proper fitting was used, whereas the earmuff and the ear canal cap were relatively insensitive to the training effect. The training was most effective for a slow-recovery foam plug over the three-week period. Results confirmed that laboratory protocols designed to simulate workplace influences on attenuation may not be relied on to yield reasonable estimates of field protection performance of HPDs, particularly for earplugs; however, the laboratory results were much better predictors of field protection for the earmuff. This study also demonstrated that the labeled manufacturers' noise reduction ratings (NRRs) substantially overestimated the actual field attenuation performance.

INTRODUCTION

Background

One of the major occupational stresses with which industrial workers must cope is excessive noise exposure. Worker compensation for occupational noise-induced hearing loss (NIHL) has become a major expense, and awards may continue to increase unless hearing conservation programs improve (Robinette, 1984).

Hearing protection devices (HPDs) are currently the most popular countermeasure against occupational hearing loss, the debilitating effects of which are insidious and irreversible. HPDs are a necessary defense when other abatement strategies such as engineer-

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ing measures (e.g., absorption and enclosures) or administrative controls (e.g., job rotation among noisy and quiet jobs) are not feasible, ineffective, or too costly.

In-Field Hearing Protection Device Performance

Although HPDs can provide effective aural defense when properly selected, administered, and used, they are not without problems in the workplace. Industrial workers often are neither properly motivated toward hearing conservation nor trained in correct HPD fitting and use; as such, they may be unable or unwilling to wear their protectors correctly. Furthermore, workers often undergo movement and exertion, perspire, and sometimes adjust or modify their HPDs for comfort rather than attenuation. Consequently, the in-field performance of HPDs is expected to be considerably less than that estimated by optimal laboratory test conditions and protocols, which typically utilize well-motivated, trained subjects who are motionless during the test, close experimenter supervision, new HPDs that are fit for high attenuation (not comfort), and a short wearing time. Such laboratory tests are used to establish noise reduction ratings (NRRs) and spectral attenuation performance data, which are required on all HPD packaging by the Environmental Protection Agency (EPA, 1990). The discrepancy between manufacturer attenuation ratings and actual workplace performance of HPDs is the subject of much controversy and has been empirically demonstrated by several field studies, most of which will be briefly reviewed.

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 generally aware that they would be subjects for the experiment but were not aware of the exact times of their tests, were taken directly from their workplace to the test facility while wearing their HPDs as found on the job. Each study attempted to establish protection levels afforded by the HPDs as used in the workplace.

Regan (1978) conducted psychophysical attenuation testing over a two-week period at a steel-stamping plant. He used the ANSI Z24.22-1957 real-ear attenuation at threshold (REAT) standard in a van-housed sound field. Regan reported that three earplugs and an earmuff (manufacturers unspecified) performed significantly poorer than indicated by manufacturers' published attenuation values. The best in-field performance was achieved by a malleable sponge earplug, followed in descending order by the earmuff, a nonmalleable rubber earplug, and a 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) determined that the field attenuation at 500 Hz of a standard V51-R earplug was considerably poorer than that of custom-molded plugs. The results contradict those of Regan (1978), who found the custom-molded plug the poorest of four HPDs. Also using a similar headphone REAT procedure, Crawford and Nozza (1981) found that premolded and custom-molded earplugs performed poorly in the field (i.e., the mean attenuations were less than 50% of the manufacturers' ratings, and standard deviations were two to three times greater than the manufacturers' values). A user-molded foam earplug, however, exhibited attenuation values closer to those of the manufacturers except at the low-frequency end of the spectrum (i.e., 1000 Hz and below).

From data obtained at six industrial plants on three earplugs (premolded twin flange, V51-R, and acoustic wool), Edwards, Hauser, Moiseev, and Broderson (1978) reported that the average worker was realizing only 33% to 54% of the potential (manufacturer rated) attenuation. A larger-scale follow-up study (Edwards, Broderson, Green, and Lempert, 1983) investigated three additional types of earplugs (foam, custom-molded, and sheathed acoustic wool) and the same user-molded acoustic wool plug used in the first study. Results from 10 plants revealed that average noise protection ranged from 9 dB at 125 Hz to 29 dB at 3150 Hz, indicating protection levels well below those published by the manufacturers.

In a Canadian field study, Behar (1985) found NRR differences between in-field and the manufacturers' ratings ranging from 5 dB (for a 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 and the earmuffs, in descending order. Most recently, a German field study (Pfeiffer, Kuhn, Specht, and Knipfer, 1989) evaluated the real-world performance of three earplugs and four earmuffs. The mean differences between field and laboratory attenuation values were 13.3 dB, 8.7 dB, and 5.9 dB for E-A-R foam, Bilsom Soft (sheathed acoustic wool), and Bilsom Propp-O-Plast (acoustic wool) earplugs, respectively. Conversely, earmuffs yielded noticeably smaller field-laboratory differences of 2.3 to 5.7 dB.

Collectively, prior in-field HPD studies indicate that the actual attenuation performance of HPDs in the workplace is considerably less than that of laboratory-obtained ratings. The current testing standard, ANSI S3.19-1974, as modified by the EPA (1990), was originally intended to yield optimal attenuation estimates for commercially available HPDs. However, in the absence of more accurate data, consumers often rely on the manufacturers' on-package attenuation values and hence run the risk of overestimating the actual attenuation afforded, thus posing 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, will help to reduce the discrepancy between laboratory and field data.

Prior Research: Laboratory Simulation of In-Field HPD Attenuation Influences

Constituting the first phase of a two-year study, a laboratory-based experiment was conducted in the Auditory Systems Laboratory at Virginia Tech as a precursor to the field study described in this paper. The laboratory study utilized protocols designed to impose certain workplace influences on attenuation, including the effects of HPD wearing time (2 h), subject activity movement (temporomandibular and simulated work-related movement), and HPD fitting procedure (*subject fit*, using only package instructions, and *trained-fit*, using experimenter guidance). The real-ear frequency-specific attenuation achieved by 40 naive subjects (10 per HPD) with a popular foam cushion muff (Bilsom UF-1), two common earplugs (user-molded E-A-R foam and premolded, triple-flanged UltraFit plugs), and the combination of the Bilsom muff worn over the foam plug was determined in a facility meeting the ANSI S12.6-1984 standard (Casali, 1988). Once fit with the HPD using the assigned fitting condition, the subject did not adjust the HPD over the full 2-h activity period. Spectral attenuation was obtained before, during (following 1 h of HPD wearing), and after (following 2 h) this period. Further details of the protocol appear in Casali and Park (1990).

Statistical analyses indicated that achieved attenuation significantly decreased over the 2-h activity period and that training the subject markedly improved protection over that obtained with manufacturer's fitting instructions alone, though these changes were device and frequency specific. Loss in frequency-specific attenuation over the activity period was up to 6.3 dB, and significant attenuation improvement attributable to user training ranged from 4 to 14 dB for all HPDs at 1000 Hz and below. There was no training effect on the achieved earmuff attenuation. The foam plug was most resistant to the effects of either type of activity movement but did benefit considerably more than the other devices from the training for proper fitting. Overall, the laboratory results indicated that trained user fitting techniques can markedly improve attenuation levels for certain insert-type HPDs. Activity movement and wearing time posed less of an influence than did poor fitting on the selected HPDs, though there was a loss of attenuation over the period for all HPDs except the foam plug.

Research Objective

Following the laboratory-based findings of Casali and Park (1990), the fundamental question remained as to how the intentionally nonoptimal laboratory attenuation results compare with attenuation achieved under real work conditions. Because both the laboratory and field studies utilized common HPDs, fitting conditions, REAT testing procedures, and subject sample sizes, the resultant data sets could be used to determine the accuracy and feasibility of applying a laboratory simulation for estimating actual in-field HPD protection. This has important implications for designing new, repeatable, inter- and intralaboratory HPD testing standards aimed at providing more realistic protection ratings.

The field investigation determined the actual spectral noise attenuation achieved by noise-exposed workers wearing selected HPDs while on the job. Specifically, we investigated the effect of HPD fitting procedure (subject fit vs. trained fit) on in-field HPD attenuation and the effectiveness of user training over a three-week period of HPD use. Not only are the results directly comparable with those from the Casali and Park (1990) laboratory simulation study, but they may also be contrasted, using summary statistics, with those from other field studies.

METHOD

Subjects

Forty paid volunteer industrial workers, all men between 20 and 59 years of age (mean, 37.9), participated in this study. They were recruited from industrial work sites near the Virginia Tech campus in Blacksburg, Virginia. The subjects, all of whom had used HPDs on the job for at least six months, read and signed an informed consent document indicating their willingness to participate.

Each subject underwent an audiometric test in accordance with ANSI S3.21-1978 (*Methods for Manual Pure-Tone Audiometry*) using a Beltone Model 114 audiometer in a sound-treated booth. 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 six out of seven pure-tone test frequencies ranging 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, in which the test signals were presented to both ears simultaneously. To obtain 40 subjects who qualified on these criteria, 46 workers were screened; 6 did not pass the audiometric requirements. Subjects also practiced the psychophysical procedures for the HPD attenuation tests during the screening session.

Noise exposure levels of the work sites were measured in accordance with Occupational Safety and Health Administration (OSHA) requirements (with a 5 dB exchange rate) using a Larson-Davis 800-B integrating sound level meter, and work sites with 85 dB(A) or higher time-weighted average (TWA) noise levels were considered for employee selection. The 85 dB(A) criterion is equivalent to OSHA's "trigger," or 50% noise dose level (OSHA, 1988). The site, measured noise level, and number of subjects were as follows:

- Coal-fired power generating plant: 90.8 dB(A) TWA, 14 subjects
- Printing press shop: 88.5 dB(A) TWA, 12 subjects
- Two metal-cutting machine shops: 87.8 and 86.5 dB(A) TWA, 5 subjects
- Carpentry shop: 98.1 dB(A) TWA, 7 subjects
- Airport: 106.4 dB(A) (measured for 15 min during taxi activity only), 2 subjects

HPD Test Facility

The sound-field facility used for all attenuation tests is in accordance with ANSI S12.6-1984 (documented in Casali, 1988) and is accredited by the National Institute of Standards and Technology. It includes an anechoic test chamber, an IBM PS/2 Model 70 computer, and an integrated Norwegian-Electronics Type 828 HPD test system. This test system, which is controlled by the IBM computer, includes signal generation, amplification, and attenuator circuits and presents one-third-octave noise signals centered at 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz through four frequency response-matched loudspeakers (TEP S-2). Using a computer-scored automatic Békésy tracking method (Békésy, 1960), each subject's thresholds were obtained for two occluded (with protector on) and two unoccluded (with protector off) trials at all nine test frequencies during each visit to the laboratory. In this manner, a spectrum of attenuation (occluded threshold minus unoccluded threshold) data was obtained.

Experimental Design

A three-way, complete factorial, mixed-factors design was used for data collection and analysis (Figure 1). Ten subjects were randomly assigned to each HPD and to each experimental cell, the only constraint being that the subject had not used the particular HPD before.

Independent variables. The three factors for the experimental design were HPD type, HPD fitting procedure, and period of HPD use. HPD type, a between-subjects variable, included E-A-R foam earplug (user-molded), UltraFit triple-flanged polymer earplug (premolded), Bilsom UF-1 foam cushion earmuff, and Willson Sound-Ban (Model 20) canal cap. The two earplugs and earmuff were the same HPDs as used in the previous laboratory simulation study, and detailed descriptions of each appear in Casali and Park (1990). The Willson canal cap is a semiaural device with round-tipped rubber pods that occlude the rim of the ear canal and are connected by a flexible plastic headband; the manufacturer's NRR is 22 dB when the device is worn under the chin, as the workers did in this study. Canal caps are often recommended for intermittent use in instances when wearers need to don and doff an HPD quickly. The canal cap was not used in the laboratory study because in pilot testing, most subjects reported discomfort in wearing it continuously for 2 h.

HPD fitting procedure was a within-subjects variable and is described in the experimental procedure section. Period of use was also a within-subjects variable, with three levels under each fitting condition: Weeks 1, 2, and 3. This variable allowed examination of the effects of practice and expe-

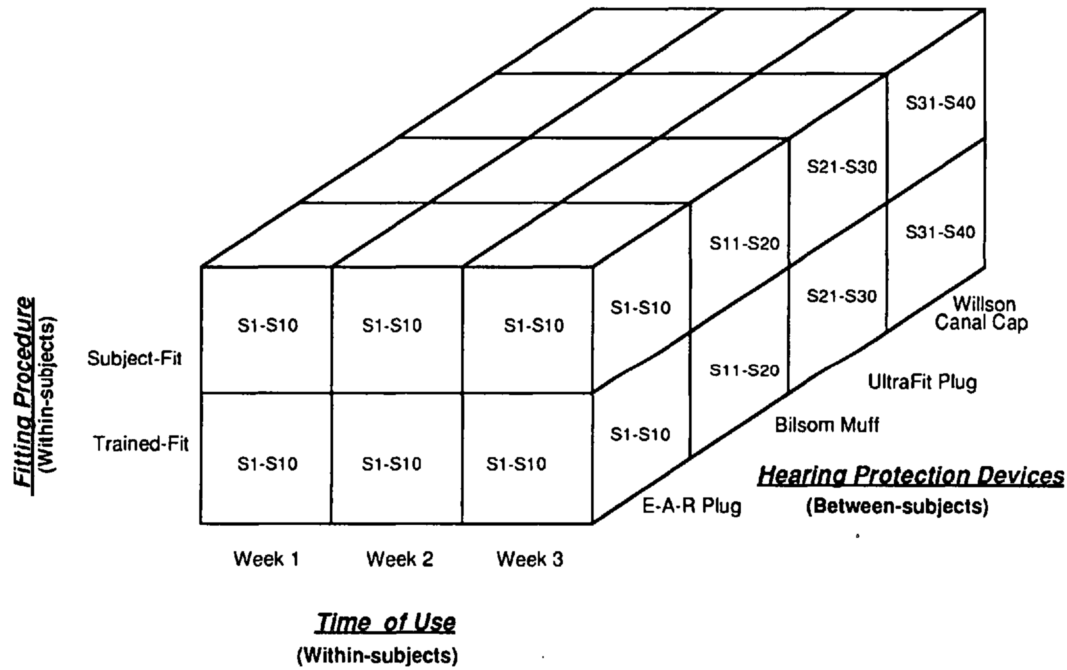


Figure 1. *Experimental design with independent variables and subject assignment.*

rience with the device over three weeks of use.

Dependent measures. Spectral attenuation values (in dB) constituted the dependent measures for all experimental conditions. For each subject in each data collection session, an attenuation score was obtained at each of the nine test frequencies.

Experimental Procedure

Each subject attended four sessions for each fitting procedure condition—the HPD fitting session followed by three data collection sessions—with at least five days between sessions. Thus across both fitting conditions, eight sessions were attended over a total six-week period.

HPD fitting sessions. For the subject-fit procedure, the first HPD fitting session was held immediately following audiometric screening and prior to the first three-week wearing period. The subject was handed the HPD in its standard industrial package and simply told to wear it while on the job for the three-week period. Only the manufacturer's package instructions were available for the subject to use in fitting the HPD. No experimenter intervention or assistance (verbal or physical) was given, and the subject was not allowed to ask any questions regarding the fitting procedures.

The trained-fitting procedure was presented prior to the second three-week wearing period—that is, after the third data collection visit with the subject-fit condition. In the trained-fit condition, 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. The experimenter did not augment the manufacturer's instructions or physically place the HPD on the subject's head. The subject practiced donning the HPD while receiving answers to questions and other verbal feedback from the experimenter.

In both fitting conditions, after the initial fitting session with the subject, no further instructions were given for the ensuing three-week wearing period.

Experimental sessions. Each of the three attenuation data collection sessions for each fitting condition lasted approximately 1 h. During the three-week use period under each assigned fitting condition, the subject was pulled from the workplace on three separate occasions (once per week) and attenuation data were obtained for the HPD as it was found to be worn by the subject on the job. Subjects did not know when they were to be tested; this was determined randomly, with the only constraint being a minimum of one week between tests. Subjects were pulled at least 1 h following the start of a workshift.

At the predetermined but unannounced time, the subject was greeted by the experimenter. The subject was informed, via a hand-held sign to preclude the necessity of talking, that he should not adjust his HPD and was then escorted to the Auditory Systems Laboratory for testing. For all subjects this was a short (i.e., maximum of 5 min) trip in an experimenter's car across campus. The subject was constantly accompanied by the experimenter and was required (in order to occupy his hands and avoid touching the HPD) to hold a set of detailed attenuation test instructions until arrival at the test chamber. Once the subject entered the test chamber, a closed-circuit television and intercom system was used to monitor and converse with the subject to ensure that no HPD readjustment occurred. These procedures enabled the collection of true workplace attenuation data under sound-field REAT protocol, representative of actual protection levels achieved by the subjects using their HPDs on the job.

In a refamiliarization procedure at the beginning of each experimental session, the subject practiced automatic threshold tracking in the test chamber. Then he underwent two occluded-ear threshold tests, removed the HPD, and underwent two unoccluded tests.

At the conclusion of each experimental session, the physical condition of the subject's HPD was checked by the experimenter. If needed, earmuffs and canal caps would have been replaced at this time, though this did not become necessary during the six-week period. Boxes containing each earplug under study were placed at each worksite, and subjects were told to replace their plugs as needed. The foam earplugs were replaced daily, whereas the premolded plugs were replaced approximately every three weeks by the subjects.

RESULTS: FIELD STUDY ATTENUATION DATA

Statistical analyses were applied to the nine one-third-octave spectral attenuation values. In addition, NRR scores were computed to enable simple HPD comparisons on a single-number rating, rather than spectral, basis.

Data Reduction

Because the results of paired t tests (with $t_{0.05}(239) = 1.97$) showed no significant ($p \geqslant 0.05$) differences between the two occluded thresholds and also between the two unoccluded thresholds at all test frequencies, the two occluded thresholds (likewise the two unoccluded thresholds) were averaged, resulting in a single pair of occluded and unoccluded thresholds for each subject in each session. Then the difference (in dB) between these two occluded and unoccluded thresholds was taken as the dependent measure at each test band frequency. The resultant data set for each experimental cell was complete, given that all 40 subjects attended all six data collection sessions. Attenuation means and sample standard deviations for each experimental condition are presented in Table 1.

Analysis of Variance (ANOVA)

Mixed-factor ANOVA procedures were applied to the frequency-specific attenuation data. Complete ANOVA summary tables appear in Park (1991); because of space limitations, only the *F* values and their significance levels are reported in Table 2. All factors were treated as fixed-effects variables in the analyses, except for subjects (S), which were random effects.

Statistically significant ($p < 0.05$) main effects were very consistent across the test frequency spectrum and were found for fitting procedure (F) at all nine frequencies and for HPD (H) at all frequencies except 8000 Hz. Significant ($p < 0.05$) interaction effects included Fitting Procedure HPD (F × H) at all frequencies except those from 2000 to 4000 Hz, Time of Use × HPD (T × H) at frequencies of 125 to 500 Hz, Fitting Procedure × Time of Use (F × T) at 2000 Hz and below, and Fitting Procedure × Time of Use × HPD (F × T × H) at 2000 Hz and below. All significant interactions and main effects were subjected to additional post hoc tests to determine the loci of significance. These post hoc analyses were performed in a "funneling" fashion, with simple-effects *F* tests (or simple interaction effects *F* tests) followed by pairwise means comparisons tests, including Bonferroni *t* or Newman-Keuls, as appropriate. Details on each of these post hoc analyses appear in Park (1991). All post hoc tests were performed at the $p < 0.05$ level unless noted otherwise. A discussion of the significant effects follows.

Fitting Procedure × Time of Use × HPD Interaction. This three-way interaction (F × T × H) was further addressed using simple interaction effect *F* tests ($F = MS_{F \times T}/MS_{F \times T \times S(H)}$) to determine if a significant F × T interaction effect on each HPD existed. According to the results, the F × T interaction changed significantly ($p < 0.05$) with both insert-type HPDs (E-A-R foam and UltraFit earplugs), whereas no significant changes were found with either the earmuff or ear canal cap.

For each of the two earplugs, further simple effect *F* tests ($F = MS_T/MS_{F \times T \times S(H)}$) were applied to investigate attenuation changes over time under each fitting procedure, followed by Bonferroni *t* tests. Figure 2, based on the Bonferroni results, 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 three-week period under the subject-fit condition, but no significant ($p \geq 0.05$) change was observed under the trained-fit condition. Conversely, the foam plug revealed a slightly different trend. Under the subject-fit condition, no significant ($p \geq 0.05$) attenuation difference occurred between the first and third week (evidenced by an attenuation loss after two weeks of use, followed by an increase in the third week back to initial attenuation levels); however, an apparent training effect of improved attenuation occurred after two weeks under the trained-fit condition.

Fitting Procedure × Time of Use Interaction. The interaction effect of fitting procedure with time of use (F × T) was also significant in the ANOVA at 2000 Hz and below. From the simple effect *F* tests, with $F = MS_T/MS_{F \times T \times S(H)}$ to determine which fitting procedure had a significant time effect and closer scrutiny with the Bonferroni *t* tests (Figure 3), a slight attenuation *loss* occurred for the subject-fit condition (an average reduction of 2.8 dB over the three-week period), but a slight attenuation *gain* was realized in the trained-

TABLE 1

In-Field Attenuation Means (Standard Deviations) in dB for Each Experimental Condition

			⅓-Octave Test Band Center Frequency (Hz)								
HPD	*Fitting Condition*	*Time of Use (Week)*	*125*	*250*	*500*	*1000*	*2000*	*3150*	*4000*	*6300*	*8000*
E-A-R foam earplug	Subject fit	1	17.0	17.8	20.0	19.4	29.5	34.3	33.3	31.7	29.8
			(9.6)	(11.5)	(12.3)	(11.7)	(10.0)	(12.5)	(11.2)	(11.3)	(9.7)
		2	10.6	10.2	12.8	14.0	23.2	27.0	26.4	25.5	24.3
			(8.9)	(11.8)	(12.7)	(13.8)	(15.2)	(14.6)	(12.3)	(14.0)	(9.9)
		3	13.5	15.1	16.9	16.9	27.0	32.3	30.3	29.3	28.7
			(11.7)	(12.7)	(15.1)	(14.6)	(14.2)	(12.1)	(11.1)	(15.3)	(12.4)
	Trained fit	1	20.5	23.9	27.2	27.6	31.1	37.4	35.8	37.8	35.3
			(9.7)	(9.9)	(11.7)	(10.6)	(6.9)	(4.8)	(5.8)	(8.3)	(8.1)
		2	26.3	28.4	33.0	32.5	34.7	38.7	38.2	40.8	37.2
			(9.2)	(9.1)	(9.2)	(6.2)	(4.0)	(3.6)	(3.5)	(9.4)	(6.0)
		3	28.2	29.6	33.2	32.3	34.9	38.5	36.3	38.5	36.3
			(5.6)	(5.8)	(7.2)	(6.0)	(3.8)	(3.1)	(3.6)	(9.2)	(6.1)
Bilsom UF-1 earmuff	Subject fit	1	9.9	13.0	19.7	25.7	26.4	34.5	35.9	37.3	34.7
			(4.7)	(3.7)	(5.3)	(7.1)	(6.5)	(3.8)	(6.0)	(7.3)	(8.2)
		2	7.6	12.4	19.3	26.3	25.2	34.1	34.8	36.2	35.9
			(4.4)	(5.1)	(5.5)	(6.9)	(6.2)	(4.4)	(7.9)	(8.5)	(7.1)
		3	7.6	11.4	19.0	27.5	26.9	34.1	37.4	37.0	35.1
			(3.4)	(4.8)	(5.3)	(6.4)	(4.1)	(2.8)	(6.3)	(5.7)	(6.3)
	Trained fit	1	8.6	12.8	20.3	26.6	28.0	37.0	38.7	37.2	35.7
			(1.9)	(2.6)	(2.5)	(4.1)	(4.3)	(3.3)	(5.4)	(5.6)	(5.3)
		2	9.8	14.5	22.0	28.0	28.3	35.9	38.2	38.4	36.4
			(2.9)	(2.7)	(3.2)	(3.7)	(3.3)	(2.8)	(5.5)	(5.6)	(6.1)
		3	9.7	14.4	20.8	27.3	29.4	36.5	38.2	37.2	36.0
			(2.8)	(3.0)	(2.6)	(3.7)	(4.0)	(2.7)	(5.2)	(5.6)	(5.9)
UltraFit earplug	Subject fit	1	14.9	15.3	15.8	17.1	22.0	26.1	23.2	19.4	21.5
			(9.8)	(10.0)	(11.6)	(11.7)	(10.1)	(10.0)	(11.3)	(11.6)	(9.1)
		2	9.8	11.9	12.4	14.5	19.0	22.6	20.0	17.2	20.6
			(7.1)	(8.9)	(8.9)	(9.9)	(9.9)	(6.7)	(7.4)	(11.0)	(13.0)
		3	4.5	5.7	7.4	9.7	16.9	22.0	19.0	16.9	17.8
			(5.7)	(6.1)	(6.9)	(8.5)	(8.2)	(5.9)	(7.0)	(9.1)	(10.8)
	Trained fit	1	17.7	18.0	19.0	20.0	25.1	28.2	28.0	30.1	33.9
			(4.6)	(5.6)	(6.1)	(5.2)	(1.2)	(5.0)	(7.3)	(7.2)	(7.5)
		2	19.1	19.8	20.9	21.1	25.5	28.4	28.1	29.9	33.7
			(3.7)	(3.3)	(2.5)	(3.3)	(3.1)	(3.0)	(5.8)	(2.9)	(5.9)
		3	19.3	20.1	19.0	22.2	27.3	28.9	28.1	30.2	32.1
			(5.5)	(6.0)	(6.1)	(5.0)	(5.6)	(4.9)	(5.4)	(6.7)	(7.6)
Willson Sound-Ban 20 canal cap	Subject fit	1	12.9	12.7	12.0	12.3	26.1	31.1	30.7	29.1	28.1
			(7.3)	(8.4)	(5.4)	(7.6)	(7.0)	(7.6)	(8.7)	(11.9)	(13.4)
		2	14.1	13.5	12.0	10.8	26.9	32.6	32.0	32.5	29.5
			(8.9)	(8.8)	(7.3)	(8.3)	(8.1)	(7.0)	(10.0)	(13.8)	(15.2)
		3	13.0	12.2	12.4	12.2	27.6	32.7	31.8	31.7	30.9
			(9.0)	(8.9)	(8.6)	(10.2)	(6.3)	(5.0)	(7.4)	(12.1)	(12.7)
	Trained fit	1	16.4	15.9	13.8	15.0	29.7	34.2	32.5	33.3	33.5
			(5.3)	(6.1)	(5.0)	(5.4)	(5.7)	(5.3)	(8.6)	(11.8)	(11.8)
		2	17.1	16.0	15.8	15.0	28.4	34.8	32.7	33.4	33.6
			(7.4)	(5.6)	(6.1)	(7.1)	(6.7)	(5.2)	(8.0)	(10.7)	(11.3)
		3	16.2	16.9	16.5	16.0	30.3	34.3	32.7	34.0	32.9
			(6.9)	(5.8)	(6.2)	(6.5)	(3.9)	(5.5)	(8.7)	(9.7)	(10.3)

TABLE 2

F Ratios for Analysis of Variance on Attenuation in dB

Source of Variance	⅓-Octave Test Band Center Frequency (Hz)								
	125	250	500	1000	2000	3150	4000	6300	8000
HPD type (H)	5.95**	3.02*	4.74**	7.66**	2.99*	7.29**	7.62**	4.89**	2.24
Fitting procedure (F)	44.17**	53.35**	53.19**	41.93**	19.32**	17.72**	18.26**	24.72**	28.06**
F × H	6.77**	7.87**	9.57**	8.37**	1.39	1.43	2.30	4.77**	4.78**
Time of use (T)	0.85	0.33	0.17	0.09	1.82	1.63	0.91	0.06	0.11
T × H	3.23**	2.80*	2.54*	1.26	0.52	1.28	0.71	0.65	1.11
F × T	16.23**	13.33**	11.56**	7.52**	4.74*	2.38	2.53	1.47	0.70
F × T × H	4.01**	3.64*	2.51*	3.29**	2.85*	1.99	1.90	1.58	1.12

* Statistically significant at $p < 0.05$. **Statistically significant at $p < 0.01$.

fit condition (an average increase of 2.3 dB over the same period) across frequencies of 2000 Hz and below.

Time of Use × HPD Interaction. This significant ANOVA interaction suggested that changes in achieved attenuation over the three-week usage period (collapsed across fitting procedures) were device specific for the lower frequencies of 125 to 500 Hz. Simple-effects *F* tests ($F = MS_T/MS_{T \times S(H)}$) were conducted on the time variable for each HPD. Only the attenuation provided by the UltraFit plug changed significantly ($p < 0.05$) over the three-week period at the low end (≤500 Hz) of the frequency spectrum. For the UltraFit plug, Bonferroni *t* tests were next employed, and the results are shown in Figure 4. Reductions in attenuation (an average loss of 4 dB below 500 Hz) over three weeks were quite consistent for the UltraFit plug, and, as previously discussed, this occurred only in the subject-fit condition. However, this reduction did not occur for the other three HPDs.

Fitting Procedure × HPD Interaction. The significant ANOVA F × H interaction effects indicated that the influence of fitting procedure on attenuation was highly device dependent, and this finding is corroborated by the laboratory-based results of Casali and Park (1990). Simple-effects *F* tests with $F = MS_F/MS_{F \times S(H)}$ were performed to examine the difference between the two fitting procedures for each HPD. Both earplugs were found to be highly sensitive to the fitting procedure effect, whereas the canal cap and earmuff were not. Comparisons of attenuation values for the earplugs 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 plug (Figure 5). The lowest and highest significant attenuation improvements attributable 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. For all devices, standard deviations (*SD*s) for the trained-fit condition were considerably smaller than *SD*s under the subject-fit condition. These interaction results, as well as the main effect of fitting procedure, clearly demonstrate the importance of training workers in proper fitting of earplugs to improve workplace protection levels.

HPD main effect. The attenuation differences found among HPDs, when collapsed across the other factors (as shown in Figure 6), were expected because it is well known that different HPDs provide a wide range of protection levels. (Of course, these results for the HPD main effect are restricted by all interactions with HPD discussed previously.) The insert protectors—especially the E-A-R foam plug—generally offered higher attenuation at lower frequencies than did the muff; however, this was not true at frequencies above 3150 Hz. The largest and the smallest *SD*s were achieved with the foam plug and the muff, respectively. One interpretation of this result is that the muff is the most straightforward to fit and therefore produces less variable attenuation across conditions, whereas the foam plug is the most complex, thereby producing more variable results under different field conditions.

Noise Reduction Rating (NRR) Data

Currently the EPA-required (EPA, 1990) noise reduction rating (NRR) is the most common single-number rating reflecting broadband HPD attenuation across a frequency spectrum. The NRR is basically 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. Using the three sets of spectral attenuation data obtained from 10 subjects on each HPD (as per ANSI S12.6-1984), NRRs for each protector under each fitting condition were calculated.

In-field NRR. For a more realistic estimation of real-world NRR, NRR_{84} scores were computed using a one standard deviation correction. NRR_{84} is an estimate of the minimum attenuation that 84% of the users of the HPD are achieving, whereas the typical NRR (sometimes called NRR_{98}) is an estimate of minimum attenuation that 98% of the user population can theoretically achieve.

The computed NRR_{84} values and computed NRR (NRR_{98}) values are presented in Table 3, along with manufacturers' reported NRRs (as of June 1, 1990) for comparison.

As evidenced in both NRR and NRR_{84} results for all of the HPDs, trained fitting procedures (which provided the highest in-field attenuation) provided noise reduction values substantially lower than those of the manufacturers. When subject fit (perhaps the most typical field condition) was used, overestimation of protection by the manufacturers' optimal NRRs was much worse.

RESULTS: CONTRAST OF FIELD AND LABORATORY DATA

A major objective of this field study was to yield attenuation data obtained with HPDs, fitting, and attenuation test environment conditions similar to those of the precursor laboratory study (Casali and Park, 1990) and thus to 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 protection levels afforded.

For each of the three HPDs common to the laboratory and field studies (E-A-R foam plug, Bilsom UF-1 muff, and UltraFit premolded plug), pairwise comparisons were made among four sets of attenuation data. These four sets resulted from the two fitting procedures in the laboratory and field studies: laboratory subject fit (LS), laboratory trained fit (LT), field subject fit (FS), and field trained fit (FT) data. Two-sample *t* tests were applied for comparisons of the LS-FS, LS-FT, LT-FT, and LT-FS pairs, which were of primary interest in these analyses. Paired *t* tests were appropriate for comparisons of the LS-LT and FS-FT pairs to further examine the fitting effect previously revealed in the ANOVA results. In summary, for each HPD of interest at each test frequency, six *t* tests (four two-sample and two paired tests) were performed.

It can be 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-h HPD wearing period (i.e., posttask

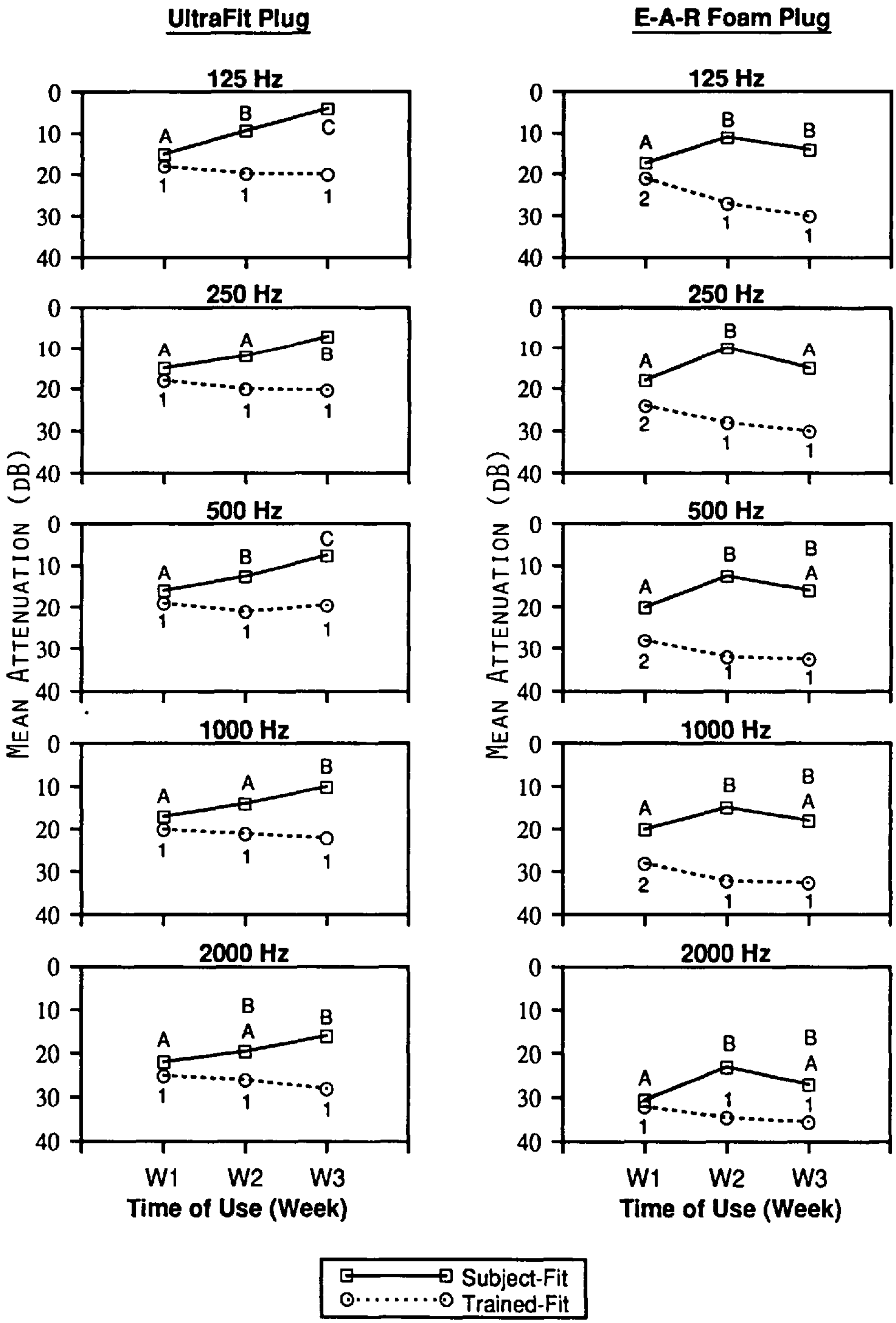


Figure 2. *One-third-octave band field attenuation over time of use under each fitting procedure for the UltraFit premolded and the E-A-R foam earplugs. (Means with different letters for the subject fit or numbers for the trained fit are significantly different at* $p < 0.05$.)

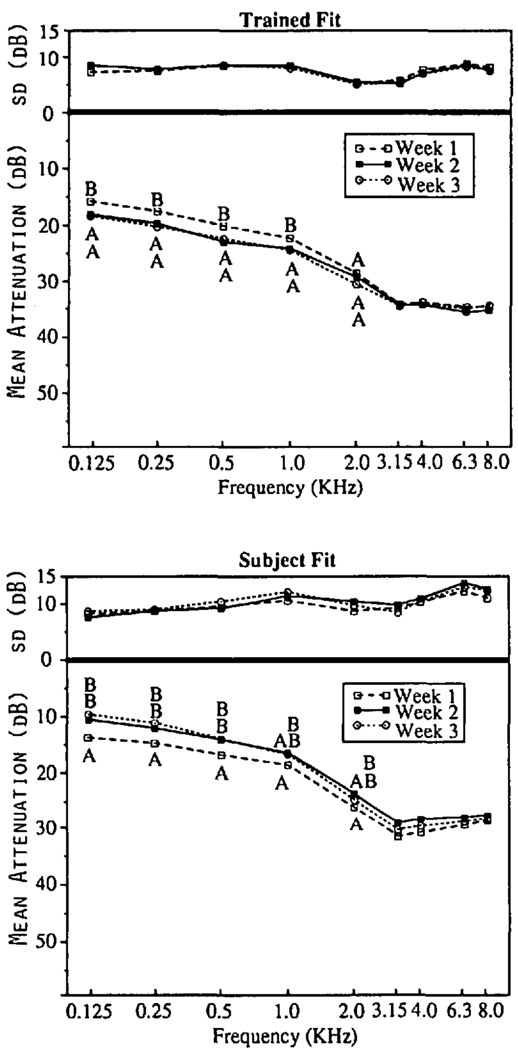


Figure 3. *One-third-octave band field attenuation over time of use under each fitting procedure. (Means with different letters in each frequency column are significantly different at* $p < 0.05$.*)*

laboratory data) might provide the most reasonable correspondence with in-field attenuation data obtained under similar fitting conditions in this study. The posttask laboratory data consistently yielded the lowest attenuation (of the three partitioned pre-, during-, and posttask laboratory data points). For this reason only the posttask portion of the laboratory data were compared with the field data using the t test comparison procedures. The results for each HPD are depicted graphically in Figure 7.

In the laboratory study the foam plug showed no pre- to posttask attenuation reductions even after 2 h of wearing time during vigorous activities. This was because the foam plug, once fit, proved very resistant to slippage as a result of wearer movement. However, the results of the LS-FS and LT-FT comparisons clearly indicated that field and posttask laboratory data sets, compared under the same fitting conditions, were significantly ($p < 0.05$) different from each other at all test frequencies. Laboratory attenuation values were considerably higher (by an average 8.3 dB for the subject-fit and 5.7 dB for the trained-fit condition) than the actual workplace attenuation achieved. No laboratory condition yielded a reasonable estimate of subject-fit field performance. The closest approximation of field performance was provided by the subject-fit condition in the laboratory, though the attenuation values produced were up to 9 dB lower (poorer) 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 h of subject movement activities, attenuation obtained in the subject-fit and trained-fit laboratory protocols was noticeably higher than that achieved with the counterpart fitting conditions in the field: an average of 10 dB and 6 dB for the subject-fit and trained-fit conditions, respectively. However, the subject-fit laboratory data (i.e., from the worst-case condition in the laboratory) did provide reasonable agreement with the trained-fit data (i.e., from the best-case condition in the field) at most frequencies (Figure 7).

In the case of the earmuff, laboratory and

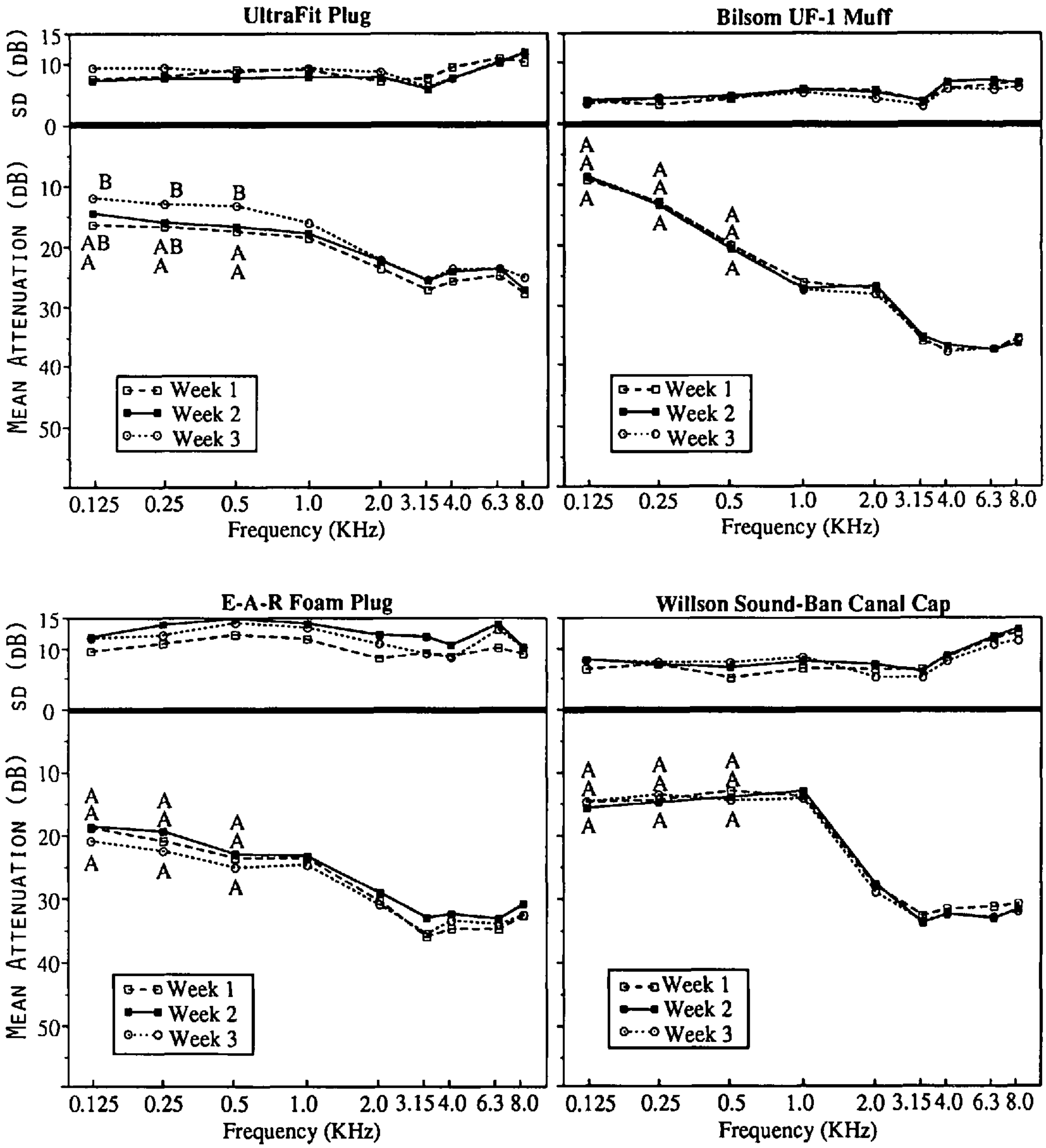


Figure 4. *One-third-octave band field attenuation for each HPD over time of use. (Means with different letters in each frequency column are significantly different at* $p < 0.05$.*)*

field results were found not to be significantly different in the LS-FS comparisons, but a few discrepancies were revealed in the LT-FT pair at 3150, 6300, and 8000 Hz. For both fitting procedures, the mean attenuation differences between the laboratory and field protocols were negligible (i.e., less 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 indicate that the laboratory work activity simulation truly mimicked the actual workplace effects on attenuation. Instead, the close agreement between laboratory and field

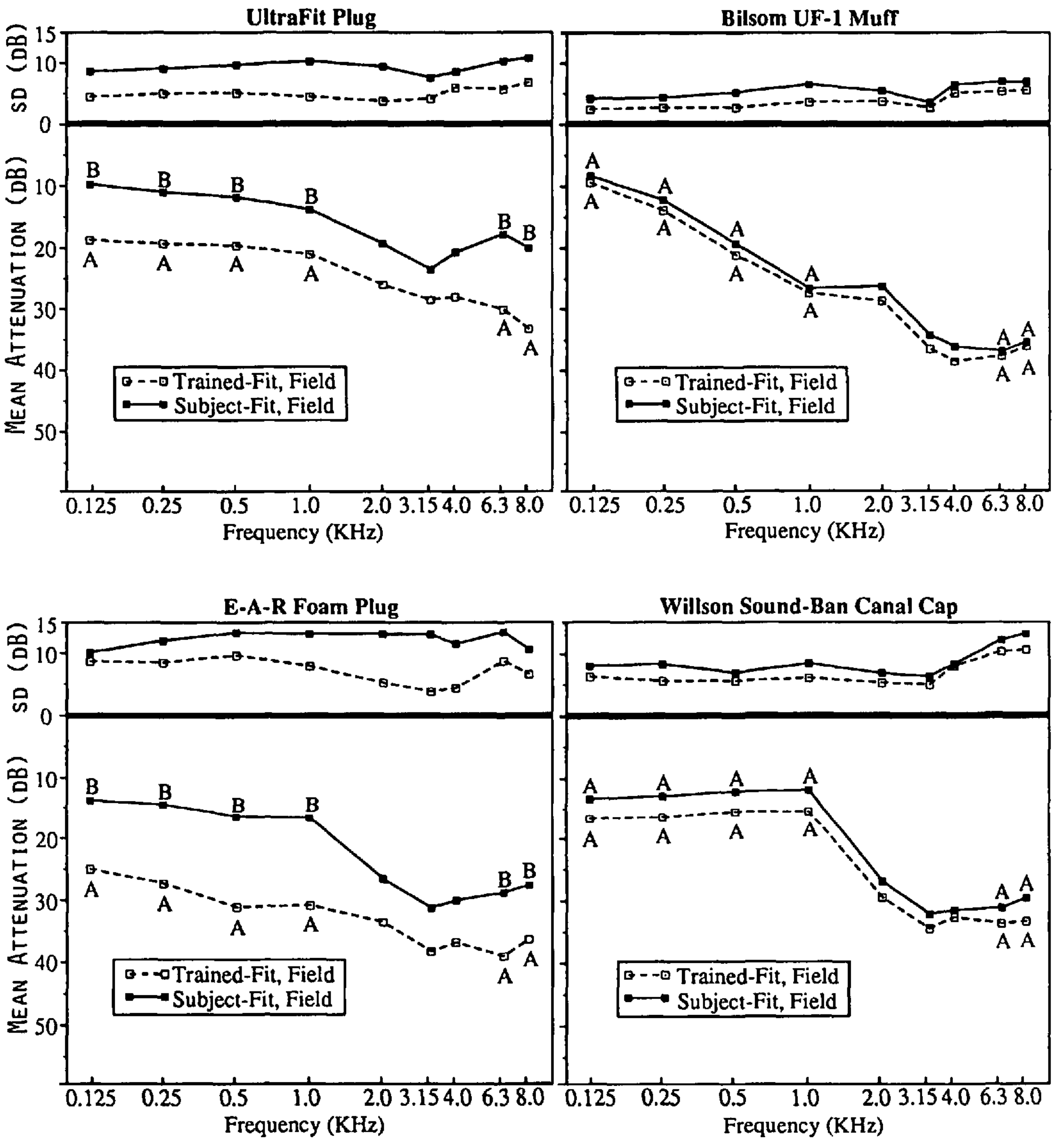


Figure 5. *One-third-octave band field attenuation for each HPD under each fitting procedure. (Means with different letters in each frequency column are significantly different at* $p < 0.05$.*)*

results for the earmuff may be attributable to the fact that this earmuff (as well as most others) is easy and simple to fit and that earmuff attenuation might not be influenced as much by certain field factors as were the plugs tested. This assumes, however, that the workers do not modify their earmuffs and that they are maintained in good condition.

DISCUSSION AND CONCLUSIONS

Importance of Proper HPD Fitting

From the fitting procedure effects (Figures 3 and 5), it is clear that with brief training for

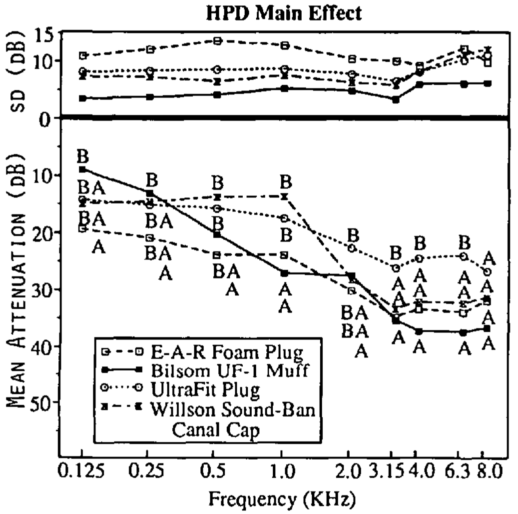


Figure 6. *One-third-octave band field attenuation for each HPD. (Means with different letters in each frequency column are significantly different at* $p < 0.05$.)

proper HPD fitting, the earplug users 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 (by demonstration) and verbal feedback was a fundamental key for attenuation improvement. However, the benefit of this training effect was highly device specific, consistently improving attenuation for the earplug HPDs but not for the earmuff or canal cap. The foam plug exhibited a more pronounced fitting procedure effect than did the UltraFit plug, particularly at frequencies of 1000 Hz and below, implying that the UltraFit plug was a relatively simpler device to fit. The patterns of the attenuation results of these two earplugs, under both of the fitting conditions in the field, generally agree with those found in the laboratory by Casali and Park (1990), in whose investigation a strong low-frequency fitting procedure effect also occurred. The attenuation improvement with training also has the important benefit that protection from the particularly hazardous high frequencies is enhanced.

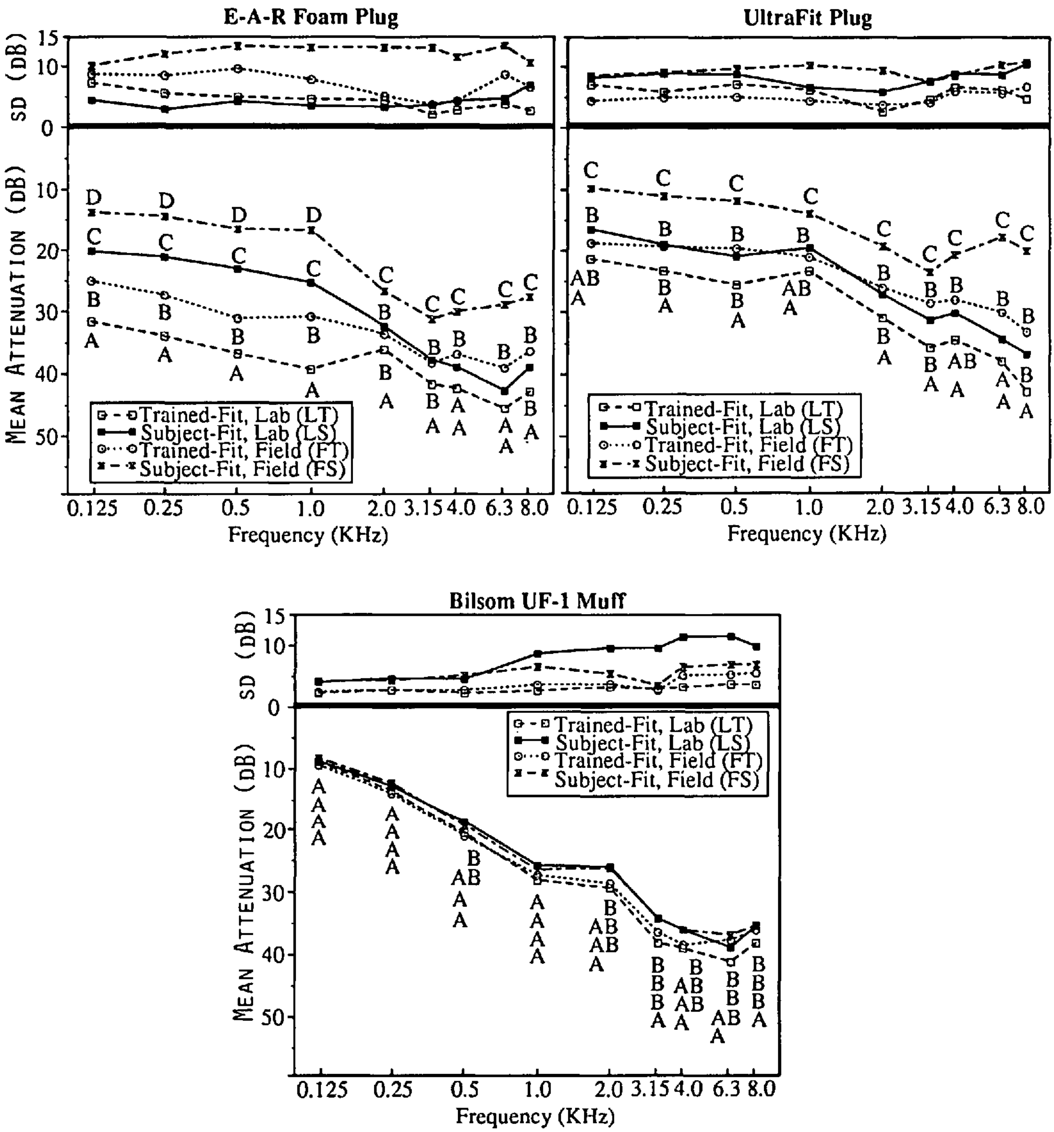
Field attenuation for the muff and canal cap, however, was relatively insensitive to the fitting procedure, and this finding corroborates previous laboratory-based results on similar devices (e.g., Casali and Lam, 1986; Riko and Alberti, 1982). Fitting procedures for both earmuff and canal cap devices are typically more straightforward than those for certain earplugs, especially user-molded foam plugs, which require more complex fitting procedures. For proper insertion of earplug HPDs, with most individuals the pinna of the ear needs to be pulled upward and outward to straighten the ear canal; this is not the case for earmuffs or most canal caps. Furthermore, to obtain a proper fit, the user-molded, slow-recovery foam plugs must be

TABLE 3

In-Field versus Manufacturer-Reported NRR Scores (in dB)

	Subject Fit	*Trained Fit*	*Subject Fit*	*Trained Fit*	*Manufacturer's*[c]
	NRR_{84}[a]	NRR_{84}[a]	NRR[b]	NRR[b]	NRR[b]
E-A-R foam plug	5.6	23.3	−7.4	15.2	29
UltraFit plug	4.3	17.0	−5.6	12.2	27
Bilsom UF-1 muff (over the head)	16.2	19.7	11.0	16.6	25
Willson 20 canal cap (under the chin)	6.4	11.9	−1.9	5.8	22

[a] Incorporates a 1 standard deviation correction. [b]Incorporates a 2 standard deviation correction. [c]Manufacturer-reported NRR as of June 1, 1990.



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

Figure 7. *Spectral attenuation comparisons of field data with posttask laboratory simulation data for each HPD. (Means with different letters in each frequency column are significantly different at* $p < 0.05$.)

compressed and rolled into a small-diameter cylinder and inserted promptly before they expand. If this is done properly, high protection values may result, as shown in the trained-fit data of Figure 5.

Field Attenuation Change over Time

Although a general trend of attenuation change over the three-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. As shown in Figure 2, in the subject-fit condition the premolded UltraFit plug lost attenuation (an average of 8 dB across 125–2000 Hz) over the three-week period. The foam plug shows relatively stable attenuation over the three-week period without training, but its attenuation did increase by an average of 2.3 dB (across 125–2000 Hz) over the three-week period with training, whereas the UltraFit plug did not show any significant training benefit over the same period. It appears that with proper initial user training, the protection of certain earplugs (especially those that require special techniques to insert) may be expected to improve over relatively short periods as workers gain experience with the devices.

Comparisons with Other Field and Manufacturers' Data

Four separate plots in Figure 8 compare the results of the subject-fit conditions of the Virginia Tech (denoted by VPI) field study (which can be considered as achieving a typical in-field fit) to other's field attenuation results and to each manufacturer's reported attenuation 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, 1988). As illustrated in Figure 8, the VPI study's field mean attenuation values fall close to the typical field data, though yielding about a 2-dB smaller attenuation across frequency than the typical results. In terms of standard deviations, the VPI field study provided consistently larger *SD*s than did the others, perhaps because of the inconsistent fit produced in the subject-fit condition and the random, unannounced retrieval of the workers for testing. When compared with the manufacturer's data, the 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, and *SD*s of this study are much greater than those labeled by the manufacturer.

Turning to the triple-flanged UltraFit plug, the typical field results used in Figure 8 were from a study that evaluated "a similar three-flanged earplug" (Berger, 1988, p. 27). The VPI field study results agree closely (in both mean and *SD* attenuation) with the other field data. Also, the attenuation differences between the field and the manufacturer values are again large, from 14.2 to 29.3 dB across the frequency range.

For the Bilsom muff, a study by Hachey and Roberts (1983) provided the only available field data for comparison purposes in Figure 8. According to the results, both field studies generally yield similar attenuation values across frequency, with exceptions at 4000 Hz and above, where the VPI study's means are higher and *SDs* slightly lower. The manufacturer's data overestimate the field attenuation by an average of 9 dB across the spectrum, with consistently smaller *SD*s.

Field performance of the Willson canal cap was compared (Figure 8) with that reported by Behar (1985), yielding generally close agreement. In comparison with the manufacturer's data, the overestimation in attenuation is an average of 13 dB across the spectrum. The *SD*s of the VPI field study are again considerably larger than those reported by the manufacturer.

Finally, field performance of the four HPDs used in the VPI field study was compared with the manufacturers' ratings using the single number NRR. The real-world NRR (i.e., subject-fit NRR_{84}) was computed for each HPD, and the resultant values (Table 3) are illustrated in Figure 9. All HPDs show large discrepancies in a comparison between the VPI field subject-fit NRR_{84} (which incorporates only a one *SD* correction) and the man-

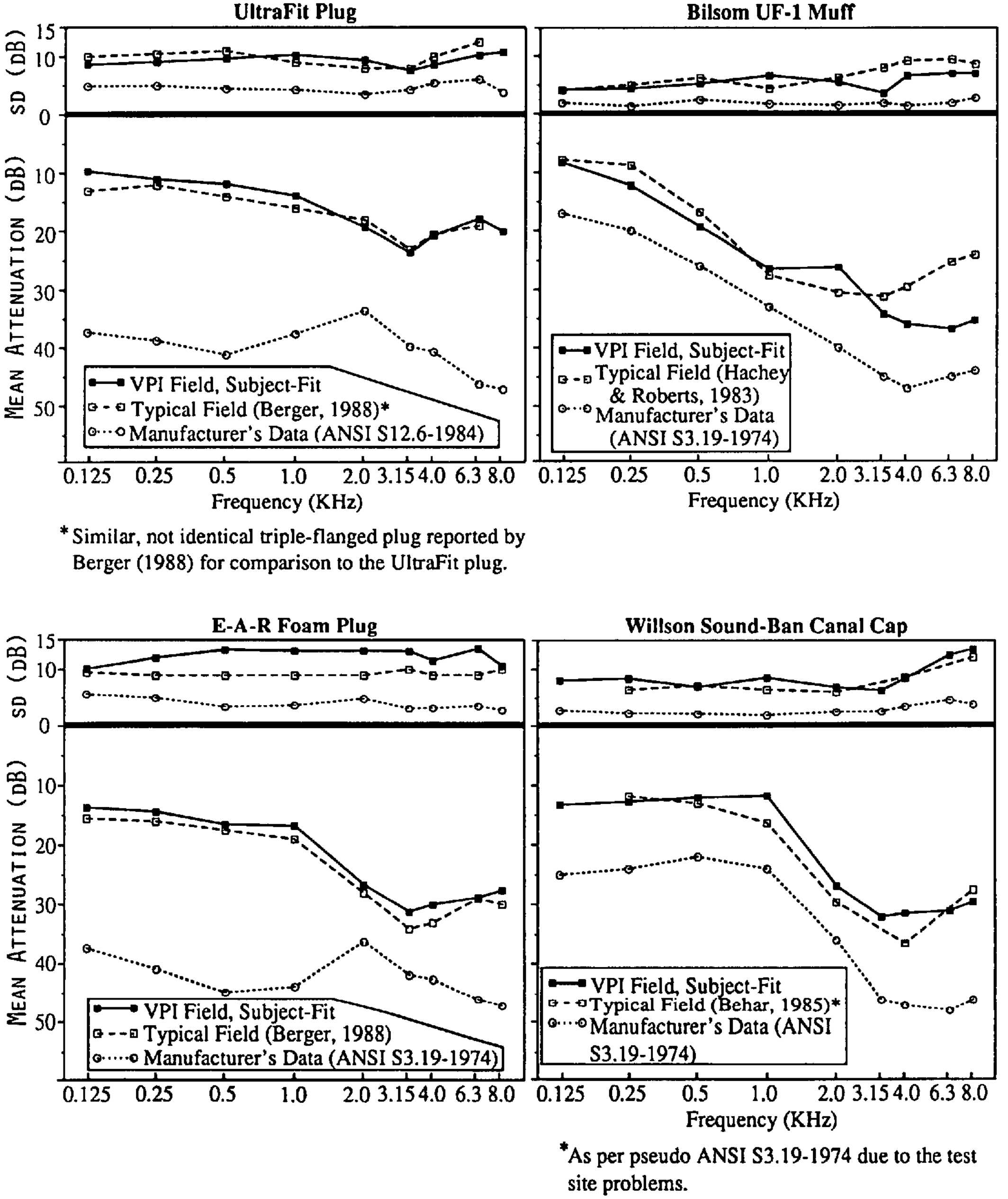
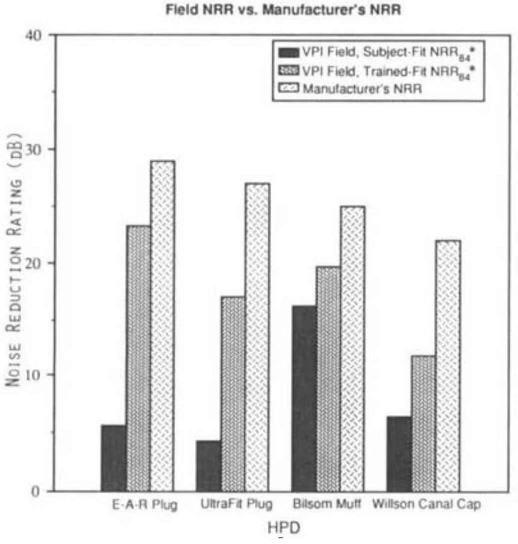


Figure 8. *Comparison of Virginia Tech (VPI) field attenuation data with other field and manufacturers' attenuation data.*



*See text for explanation.

Figure 9. *Comparison of Virginia Tech (VPI) field NRR_{84} scores with manufacturers' NRR values.*

ufacturer's NRR (which incorporates a two *SD* correction). The subject-fit field versus laboratory differences are largest for the foam plug (by 23.4 dB), followed by the premolded UltraFit plug (by 22.7 dB), the Willson canal cap (by 15.6 dB), and the Bilsom muff (by 8.8 dB). Although foam plugs have been reported to have the highest in-field attenuation of any earplugs used (Berger, 1988), the current data for the foam plug yielded a field NRR_{84} of only 5.6 dB in the subject-fit condition (primarily because of large *SD*s). However, the NRR for both earplugs improved dramatically when subjects were trained to insert the devices properly.

Validation of the Laboratory Simulation Study

As discussed previously, to determine the accuracy and validity of the laboratory simulation study (Casali and Park, 1990), the results of this field study were compared with the laboratory simulation data. As depicted in Figure 7, the two earplugs used for comparison showed consistently higher mean attenuation under the laboratory than under the field experimental protocols for the same fitting conditions, indicating that the laboratory work activity simulation could not sufficiently account for all of the workplace influences. Comparisons with the worst-case laboratory data (i.e., posttask) demonstrated significant differences between the two settings. 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 plug. Although the earmuff's attenuation generally provided good agreement between the two laboratory and field settings, the results from the two earplug devices strongly suggest that laboratory simulation data cannot be used as an accurate indicator of real-world attenuation measures when similar fitting conditions are used in both settings.

IMPLICATIONS AND RECOMMENDATIONS

The results of this field study highlight the significance of the training effect in the industrial workplace; therefore, careful HPD selection and user training for better HPD fitting should be provided to workers to help them achieve adequate hearing protection. Motivational strategies should also be implemented along with the training. In addition, because industrial trainers' knowledge and skills in HPD fitting may be lacking, those personnel need to be trained appropriately in advance by a qualified individual.

The attenuation results imply that it is difficult to devise a behavioral, repeatable laboratory simulation protocol that yields realistic estimates of real-world HPD attenuation, particularly for insert-type devices. Because the field data from this and other studies provide attenuation estimates well below the levels reported by HPD manufacturers (as well as below those of the posttask laboratory results), derating schemes have been suggested for reducing the NRR before subtracting it from workplace protection levels. One such suggestion in OSHA (1983) is to reduce the NRR by 50% when comparing relative attenuation of HPDs and other controls. However, at this stage it is not possible to devise a precise, global derating scheme that would be appropriate for all devices. Whereas a 50% derating may be accurate for some HPDs, it penalizes certain devices unfairly. For instance, based on the NRR_{84} data from this study, a derating of 20% to 35% for the Bilsom earmuff would be more accurate.

In addition, more realistic laboratory test protocols that closely reflect field conditions need to be developed and tested. Currently an American National Standards Institute working group (ANSI S12/WG 11) has devised several alternative test procedures and is evaluating their validity. When such protocols are fully developed and implemented in an HPD test standard, the need for specifying a low NRR to high NRR *range* for each HPD may be necessary, based on the findings of this study.

Unrealistically high laboratory-based attenuation values should be of concern. First, the manufacturers' labeled attenuation data are generally the sole information that the consumer has to rely on when selecting a new or unfamiliar device. In seeking the best protection, the consumer's tendency is to choose HPDs with the highest NRRs, without considering other factors such as comfort and compatibility with the relevant environment. However, because the devices are tested under fitting conditions that promote attenuation, not comfort, the highest-attenuation HPDs may not yield the best protection in field use because of periodic readjustment or, worse, nonuse by the worker who finds them uncomfortable. Second, if the NRRs are accepted at face value (and they often are in the absence of any guidance for derating), the consumer is led into a false sense of security that nearly any HPD will provide adequate protection in almost any noise that might be encountered. The average NRR (i.e., 23) across available devices (from Gasaway's 1988 compendium) should theoretically protect in up to 108 dB(C) (85 dB(C) + 23 = 108), which is at the high end of typical 8-h industrial exposures. However, this assumes that the HPD is working optimally. In the estimated 92% of industrial exposure situations that comprise 8-h equivalent levels of 95 dB(A) or below (OSHA, 1981), some available HPDs will achieve the necessary attenuation to reach acceptable protected levels by OSHA regulations. However, considering that many industrial noise exposures are above 95 dB(A) for 8 h and that military cannon and explosives testing often entail very high peak sound pressure levels (e.g., 140 dB and above), the safety margin needed in attenuation to avoid noise-induced hearing loss becomes more critical. Furthermore, in these environments, the ramifications of inaccuracies in attenuation estimates are quite serious.

ACKNOWLEDGMENTS

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