



**EFFECT OF INDUSTRIAL WORK-RELATED VARIABLES
ON ACHIEVED HEARING PROTECTOR ATTENUATION**

by

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LIST OF ABBREVIATIONS

ANOVA: analysis of variance

ANSI: American National Standards Institute

AT500: Attenuation measurement at 500 Hz

dBA: decibel (dB) level with A-weighted filter

dBC: decibel (dB) level with C-weighted filter

dBHL: hearing threshold level in dB

EPA: Environmental Protection Agency

FS: field subject-fit

FT: field trained-fit

HPD: hearing protection device

IBM PC: International Business Machines Personal Computer

LS: laboratory subject-fit

LT: laboratory trained-fit

NRR: Noise Reduction Rating

NRR₈₄: NRR calculated with a 1-standard deviation correction

NRR₉₈: NRR calculated with a 2-standard deviation correction

NRR_{PS}: NRR Per Subject
(NRR calculated with no standard deviation correction)

PI: prediction interval

OB: octave-band

OSHA: Occupational Safety and Health Administration

REAT: real-ear attenuation at threshold

SD: standard deviation

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3. Based on the previous two findings, there is considerable evidence that with poor protector fit and/or during vigorous wearer activity, the risk of compromised hearing protection and OSHA noncompliance increases. Proper device selection and user training help to ensure that the maximum protective benefit is obtained in the industrial setting. However, even with such efforts, the field results indicate that the Noise Reduction Ratings (NRR) actually realized in the workplace are generally much lower than those printed on protector packaging. On average across the four devices tested, the actual field NRRs were less than one-half of the labeled NRRs. When trained-fit procedures were used, the differences were largest for the canal cap and smallest for the earmuff. However, when workers fit their devices with no training other than the manufacturer's instructions, the field versus labeled NRR differences were largest for the two earplugs, ranging from differences of 9 to 36 dB, depending on the standard deviation corrections used.

4. Over a three-week usage period in the field study, there was no large change in attenuation afforded by the four devices. However, when subject-fit procedures were used in an initial session with the workers, the attenuation tended to drop slightly (average of 2.8 dB) over the period. When training was used in the initial session, there was a slight gain in attenuation over the three-week period as subjects gained practice with the proper fitting techniques.

5. The overall field attenuation results, when statistically compared with those of the precursor laboratory study, generally indicate that laboratory protocols cannot be relied upon to yield valid predictions of true workplace protection levels afforded by hearing protectors. The post-task laboratory results, which were closest to those from the industrial workplace both in accuracy and conditions obtained under, were still disappointing in their correspondence with actual protection levels. The exception was the earmuff, for which the laboratory results were not significantly different from those of the field at any frequency when like fitting protocols were compared. However, there were large discrepancies between laboratory and actual field average spectral protection for the two earplugs: 8.3 dB for subject-fit and 5.7 dB for trained-fit for the foam plug; 10 dB for subject-fit and 6 dB for trained-fit for the UltraFit plug. The only close correspondence between laboratory and field results for the earplugs was that the subject-fit results from the laboratory provided a reasonable prediction of trained-fit

field attenuation for the UltraFit. These findings collectively indicate the inappropriateness of using laboratory-derived attenuation ratings for estimation of the protection levels actually afforded by insert protectors in the dynamic workplace.

6. 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 best for the Bilsom muff followed by the UltraFit plug, but were sufficiently accurate for all devices to enable an estimate of the broadband protection obtained by the worker, based solely on a quick, single-frequency audiometric measurement.

7. Standard laboratory protocols (e.g., ANSI S3.19-1974; ANSI S12.6-1984) for measuring hearing protector attenuation require revision if realistic influences on protection levels are to be accounted for in labeled noise reduction ratings. As they now are obtained, these ratings substantially overestimate the actual protection afforded in many hearing conservation programs, appear to offer highly device-specific accuracy, and are problematic for the industrial safety end-user. Therefore, the labeled ratings cannot be depended upon to ascertain actual protection achieved, *only protection potentially-achievable*, and may offer only a compromised, albeit common, means of inter-protector comparison since the ratings are better predictors of field performance for some devices than others, as demonstrated in the field study.

8. The perceived comfort afforded by the foam earplug was significantly higher under subject-fit than under trained-fit. However, the earmuff and ear canal devices were insensitive to the fitting effect.

9. Among the four single HPDs, the most and the least comfortable, judged by the laboratory and field subjects, were the foam earplug and the ear canal cap, respectively. There were significant differences between the laboratory and field subjects' comfort ratings for the earmuff and the premolded earplug, suggesting that the true determinant of comfort is the HPD's performance on a daily basis when worn for long periods.

ABSTRACT

Two studies, each using 40 subjects and 4 hearing protection devices (HPDs), of which 3 were common to both studies, were conducted to determine spectral noise attenuation and perceived comfort in controlled laboratory and industrial field settings. The laboratory simulation protocol, which elicited activity movements akin to those performed in the typical industrial workplace, was developed to investigate the effects of several field factors of HPD wearing time, activity movement, and HPD fitting condition, on spectral attenuation and comfort afforded by foam and triple-flanged earplugs, a foam-cushion earmuff, and an earmuff over foam earplug combination. Using a computer-controlled, psychophysical real-ear-attenuation-at-threshold (REAT) procedure (as per ANSI S12.6-1984), attenuation data were obtained before, during, and after the activity movement tasks. Bipolar comfort rating data were also collected before and after the activity movement tasks.

The results of statistical analyses indicated that achieved attenuation and user comfort significantly decreased over the two-hour HPD wearing period and that training for better fitting markedly improved the noise protection: loss in spectral attenuation with the wearing period was up to 6.3 dB for all HPDs except the foam earplug, which exhibited a unique resiliency to attenuation loss due to activity movements over the wearing period; and significant attenuation improvement due to training ranged from 4 to 14 dB at the low frequency spectrum (1000 Hz and below) for all earplug HPDs (including combination protectors) except the earmuff. The earmuff, which was resistant to fitting effects on attenuation, tended to slip during highly kinematic head/torso movement, though almost no significant difference in achieved attenuation or comfort was found between the two activity movements. The earplugs provided consistent comfort over the period but were very sensitive to fitting effects.

Turning to the field study, which used the same REAT procedure, fitting conditions, bipolar comfort rating scales, and 3 HPDs (the 2 earplugs and earmuff) used in the laboratory study (but with an additional ear canal cap), the actual noise attenuation and comfort were obtained over 2 consecutive 3-week periods of HPD use in 5 industrial workplaces. In general, similar results to those of the laboratory study were found for earplugs' benefit on attenuation improvement with training: gain in frequency-specific

attenuation due to training ranged from 7.2 to 14.6 dB, depending on the frequency and the earplug. The training was most effective for the foam plug over the 3-week period. However, as expected on the basis of the laboratory results and previous research evidence, the earmuff and the ear canal cap devices were consistently resilient to the training effect. When data were collapsed across HPD, during the 3-week use of HPD, slight attenuation loss (an average of 2.8 dB over the period) was noticed in the subject-fit condition; on the other hand, slight attenuation gain (an average of 2.3 dB over the same period) was realized in the trained-fit condition. The study also confirmed that the labeled manufacturers' noise reduction ratings (NRRs) substantially overestimate the actual field NRRs under the subject-fit condition (which is perhaps the most realistic field condition). The perceived comfort of the earplugs (particularly the user-molded foam earplug) was significantly higher under the subject-fit procedure; however, this did not occur for the earmuff and the ear canal cap devices, as was borne out in both the laboratory and field attenuation results. This insensitivity to the fitting effect is probably due to the fact that circumaural and semi-aural devices are generally more straightforward and easier to wear than insert-type HPDs.

To ascertain the validity of estimating field HPD performance in a laboratory simulation protocol, both attenuation and comfort data from the two settings (field vs. post-task laboratory) were statistically compared under each fitting condition for the three common HPDs to both studies. The results from attenuation comparisons demonstrated that significant differences existed between the 2 protocols for 2 (the earplugs) out of the 3 HPDs: average attenuation differences between the two settings were 8.3 dB (under the subject-fit) and 5.7 dB (under the trained-fit) for the user-molded foam plug, 10 dB and 6 dB, respectively for the premolded UltraFit plug. The comfort comparison results showed significant differences between the laboratory and the field comfort ratings for two (the earmuff and the UltraFit plug) out of the three HPDs. From these comparison results, it is concluded that both attenuation and comfort performance of HPDs achieved in laboratory simulation protocols may not be relied upon to yield very accurate predictions of field attenuation and comfort obtained on the job, though certain HPDs (e.g., earplugs in attenuation comparisons) provided more accurate estimates of field performance than others. Standard laboratory protocols (e.g., ANSI S3.19-1974; ANSI S12.6-1984) for measuring hearing protector attenuation require revision

if realistic influences on protection levels are to be accounted for in labeled noise reduction ratings.

EXTENDED SUMMARY OF ATTENUATION RESULTS: LABORATORY AND FIELD STUDIES

INTRODUCTION

Hearing Protectors and Their Effectiveness

Personal hearing protection devices are often used to combat the insidious threat of noise-induced hearing impairment in individuals who undergo sound exposures of hazardous intensities and durations. Relied upon primarily in industrial and occasionally recreational settings, many styles of aural (earplugs), semi-aural (ear canal caps), and circumaural (earmuffs) are currently available to reduce airborne sound levels at the eardrum of the user.

In U.S. industry, hearing protection devices (hereafter HPDs) have emerged as the most popular long-term countermeasure against noise exposure effects, largely because of the expense, ineffectiveness, and/or infeasibility of alternative strategies such as engineering controls and administrative interventions. In fact, the Occupational Safety and Health Act (OSHA) has solidified the need for effective HPDs with the requirement that all employees exposed to a daily time-weighted mean of 85 dBA or greater be *supplied with a choice* of HPDs which provide adequate attenuation for the noise at hand (OSHA, 1988). Environmental Protection Agency (EPA) estimates indicate that over 9 million American workers are exposed to these levels, with over 5 million in manufacturing and utilities industries alone (EPA, 1981).

HPD testing and labeling. While HPDs can be an effective deterrent to hearing loss when properly selected and used, a major problem exists with the laboratory-based ratings of their protective performance. These spectral attenuation statistics (means and standard deviations) and the noise reduction rating (NRR), which is computed thereof, are obtained using psychophysical tests on qualified human listeners. The ratings are the primary means by which end-users compare different HPDs on a relatively common basis and then make selections of specific devices to provide ample protection and OSHA compliance in a given high-noise environment. But the standardized test protocol (ANSI S3.19-1974) required by the EPA (1985) for obtaining real-ear attenuation data used for product labeling purposes is clearly biased toward yielding "optimum protector performance" data (ANSI S3.19-1974, p. 5).

Therefore, the test standard produces unrealistically-high estimates of typical attenuation actually afforded.

Highly controlled laboratory tests performed according to this standard in no way account for workplace influences on HPD performance. In such tests, highly trained and motivated subjects are seated quietly for a very short wearing period and tested with new protectors. Furthermore, the EPA regulations stipulate that the experimenter will check the fit of the HPDs "to assure a good fit and acoustic seal," and then he/she can reinsert or readjust protectors to a "best" fit before testing commences (EPA, 1985, p.130; ANSI S3.19-1974, p. 5). In contrast to these optimal test conditions, users in the field may wear ill-fitted and/or damaged HPDs for prolonged periods and while performing physical movements and exertions associated with the work activities, all of which may compromise the protector's seal against noise.

Another factor contributing to the laboratory test versus field discrepancies is that of comfort. During the tests, HPDs may be fit on subjects without regard to their comfort but instead to achieve optimum attenuation. For example, earplugs may be inserted by an experimenter more deeply in the ear canal of a subject for testing purposes than would an individual on himself for daily use. While the experimenter-fit protocol may help yield "optimal protector performance," this performance must not be construed as an accurate indicator of protection that is typically achieved in the real-world.

Clearly, the standard procedures and conditions under which HPDs are tested and rated are quite different than those in the environments of actual use. In essence, the current testing standards are invalid for the prediction of HPD protection performance in the bulk of workplaces, unless a reduction or "derating" is applied to the resultant attenuation. Several such derating schemes have surfaced in the literature; one is to reduce the NRR by 10 dB before subtracting it from the measured C-weighted sound level of the offending environment (Berger, 1983). Field surveys have provided empirical evidence confirming that laboratory-obtained attenuation values indicate significantly higher protection than is typically obtained in-field (e.g., Lempert and Edwards, 1983; Padilla, 1976). Based on a review of these surveys, Berger (1983) concluded that the NRR overestimated actual protection by an average of 13 dB or more. Considering that the

mean of published NRRs for most currently available HPDs is approximately 23 (based on 402 devices in Gasaway's compendium of 1988), a 13 dB error results in an unacceptable protected level of 92 dBA in noise of 95 dBA and above, which is a very common industrial level. $\{95 - [(23 - 7) - 13] = 92 \text{ dBA}$; where 90 dBA 8-hour average is the OSHA threshold at which HPDs must be worn, and where OSHA requires that the NRR be reduced by 7 dBA when the ambient noise is in dBA rather than dBC (OSHA, 1988).)

Should these unrealistically high noise attenuation values be of concern? Yes, for several reasons. 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. With the "best" protection in mind, the consumer's tendency is often to choose HPDs with the highest NRRs, without regard to other factors such as comfort and compatibility with the environment of interest. However, since the devices are tested under fitting conditions which promote attenuation, not comfort, the highest attenuation HPDs may not yield the best protection in field use due to periodic readjustment, or worse, non-use, by the user who finds them uncomfortable. Second, if the NRRs are accepted at face value, the consumer is led into a false sense of security that nearly any HPD will adequately protect in almost any noise which might be encountered. This is particularly the case in industrial situations in which the average NRR (i.e., 23) across available devices should theoretically protect in up to 108 dBC $\{85 \text{ dBC} + 23 = 108\}$, which is probably at the high end of typical 8-hour industrial exposures. However, this assumes that the HPD is working optimally. It is plausible that in the 92% of industrial exposure situations which comprise 8-hour equivalent levels of 95 dBA or below (OSHA, 1981), some HPDs will achieve the necessary attenuation to reach acceptable protected levels by OSHA regulations. This conclusion is based on the collective results of 10 field studies which indicated that on average, earmuffs provide 10-12 dB and earplugs (excluding foam plugs) less than 10 dB of protection in the workplace (Berger, 1983). But as noise exposures increase in level and/or duration beyond 95 dBA for 8 hours, the safety margin needed in attenuation becomes more critical.

Another problem with unrealistically high attenuation data for device labeling purposes emanates from the propensity for high NRRs and competitive prices to be major factors in the market success of an HPD. Thus, the competitive need for a high NRR can pit

manufacturers against each other in the product testing arena. In reality (and not disallowed by the current testing regulations), multiple attenuation tests can be performed on a single HPD and the results from any of them used as a basis for labeling purposes. Because the final NRR value depends on spectral means and standard deviation values from a minimum of only 10 subjects, it can fluctuate wildly due to only one or a few outlier observations within the sample. Therefore, redundant tests (usually at considerable expense for each) may be performed until one is satisfied that the "optimum" NRR value is obtained. These and other related sampling phenomena which influence attenuation results certainly promote the use of multiple tests to obtain an optimum NRR for product labeling.

Finally, the publication of attenuation ratings that are not valid for the actual conditions of HPD usage may foster a basis in part for civil litigation. Buyers and users of HPDs expect that the devices provide sufficient protection and may, albeit often incorrectly, rely on the NRR as a realistic measure of that protection. Under tort litigation, individuals who experience a hearing loss as a consequence of noise exposure may attempt to assign blame to those responsible for selecting and fitting the HPDs, and ultimately, may name the HPD manufacturer as a defendant on the basis of advertised attenuation ratings. With the increasingly litigious nature of our society, this potential for inflated NRRs to serve as a partial basis for claims should not be taken lightly.

Achieving More Realistic HPD Attenuation Estimates

There is no question that product labelings of data on HPD attenuation performance is misleading and should be more accurate and valid for the actual environment of use. For more accurate data to be realized, one of two approaches, or a suitable hybrid of both, must be adopted. It is clear that current HPD testing standards are not designed to yield attenuation data that can be applied to field use. Therefore, one strategy is to develop new (or revised) testing protocols. It seems imperative that any standardized testing procedure be implemented in a laboratory environment so that conditions and procedures can be controlled and replicated. However, the very essence of testing in a laboratory centers upon experimental controls which do not allow for the inclusion of all possible field influences. Thus, there is a strong possibility that no laboratory procedure will yield attenuation data that truly reflects

typical performance of HPDs in the field. For this reason, the second approach, that of "derating " laboratory-obtained values, may be necessary as well. For derating NRRs obtained under the current testing regulations, no agreed-upon, real-world correction factor exists. A strong case has been made by Berger (1983) suggesting the use of a 10 dB derating of the NRR before subtracting it from the dBC noise level in which the HPD is used. However, this correction factor is purposely smaller than the average difference found between real-world and laboratory attenuation performance, and because it is an averaged value itself, it is not directly applicable to all individual HPDs. With a range of NRRs from 6 to 35 dB (Gasaway, 1988), it is readily apparent that no single number derating factor is appropriate. For any derating scheme to provide utility across devices, it must comprise percentage or proportional correction factors which vary with the NRR and perhaps with other field influences which are more difficult to specify.

Whether a derating scheme, a new test standard, or both are used, one thing is certain: the type of target field hearing conservation program for which the attenuation estimates must be representative requires specification. Since actual HPD performance depends heavily on the commitment to hearing conservation within the company, and because laboratory estimates of performance have tended to be high, perhaps HPD testing efforts should strive to yield data which are accurate for situations where an active, quality conservation program exists.

Because current NRRs tend to overestimate in-field protection by such a sizable amount (13 dB on average according to Berger, 1983), efforts to develop new test standards and device labeling regulations are in order. Derating schemes have some utility and may prove necessary in the final outcome, but it seems counterproductive and unscientific to endeavor to obtain data that is product-specific and then, in post-hoc fashion, attempt to artificially transform those data into a more representative set by applying a universal derating factor. Furthermore, for some low-to-medium attenuation devices, the previously-suggested correction factor is more than one-half of the HPD's rated attenuation, attesting to the gross overestimation of the standard test results.

Research Objectives

A two-year research program was devised to examine the major issues associated with testing HPDs in laboratory environments and applying the results to actual protector usage in the industrial field setting. Both attenuation performance as well as subjective user comfort were investigated. The major attenuation results are discussed herein, while the comfort findings appear in the "comfort" manuscript (Park and Casali, 1990a) in Appendix I of this report. Two experiments comprising similar independent variables were conducted during each of the two project years; a laboratory study was performed during the first year and a comparable field study, on a different subject pool, was conducted during the second year. The field study enabled the laboratory attenuation results to be compared with actual protection levels achieved with identical HPDs in the industrial setting.

The intent of the laboratory study was to bring several potential workplace influences into a controlled setting to ascertain the magnitude of effect of those influences on HPD attenuation as tested using human subjects. Specifically, a laboratory-based protocol was developed and utilized to examine the effect of two important real-world variables (HPD fitting procedure and movement activity during the wearing period) on the achieved attenuation of four different HPDs. These two variables were selected because current HPD testing standards provide protection ratings only for a well-supervised fit of the HPD immediately after the device is donned, which is unrealistic in the application setting. In effect, the laboratory experiment was aimed at developing a behavioral, yet repeatable protocol which simulates real-world effects on attenuation and investigating the viability of using that protocol in an attenuation test. In other words, the laboratory protocol used can be thought of as a "degraded" standard testing protocol, with the intent of providing more realistic and field-achievable attenuation performance results.

LABORATORY INVESTIGATION

Experimental Method

Design. Four groups of 10 (5 male and 5 female, aged 19-35 years) subjects, who were non-users of HPDs prior to entering the study, were assigned to one of four HPDs which were representative

of the four major categories of industrial protectors, i.e. user-molded and premolded earplugs, earmuffs, and "double-protectors" (muffs over plugs). Several ear canal caps were also pilot-tested, but these were eventually dropped from the study because subjects complained that they were too uncomfortable to wear continuously for the required two-hour wearing period. With the exception of the HPD variable, which was between-subjects, each of the 40 subjects underwent all levels of the other independent variables. The four factors investigated in the laboratory study were:

1) *HPDs* (model and NRR at time of study): a) Bilsom UF-1 foam cushion earmuff, NRR=25 when worn over-head; b) E-A-R slow-recovery foam earplug, NRR=29; c) E-A-R UltraFit premolded polymer earplug, NRR=27; and d) Combination, Bilsom muff over E-A-R foam plug;

2) *fitting procedure* : a) subject-fit using only manufacturer's on-package instructions and no other assistance from the experimenter, and b) trained-fit with experimenter-provided verbal feedback (no physical assistance) and a 70 dBA pink-noise for subjective determination of a good seal;

3) *movement activity* : a) temporomandibular movement consisting of alternating 5-min periods of chewing gum or eating a snack with 5-min periods of reading aloud with a 70 dBA forced vocal effort, and b) work activity movement consisting of 3-min periods of highly kinematic exercise on a Baltimore Therapeutic Work Simulator and rapid side-to-side head movements to monitor displays, separated by 2-min rest breaks, with both types of activities performed for two 30-min periods; and,

4) *wearing period* : corresponding to the time juncture of when the attenuation measurements were made for a single fitting of the HPD, either 0 (pre-task), after 1 hour (during task), or after 2 hours (post-task).

It should be noted that the selection of the levels of the independent variables was made to provide a representation of a range of realistic influence on HPD performance. For instance, the two fitting conditions were intended to span the extremes of fitting instruction found in industry. That is, in the worst case, workers are left to don their HPDs with no guidance or supervision, and in the

best hearing conservation programs, workers are given close instruction and feedback on their HPD fitting techniques. In the case of the movement activities, it is common to use hearing protection while chewing gum or tobacco, eating, or talking, all of which cause some distortion of the ear canal or movement of the facial bones, which may affect the HPD's seal. Likewise, the work-related movement activities were designed to provide a realistic experience of vigorous physical movements of the head and torso which are common in many industrial jobs and which may dislodge a protector.

Protocol. Each subject was first screened using a Beltone Model 114 manual audiometer, and required to have dBHL (hearing threshold levels) between -10 and 20 dB at frequencies of 125 to 8000 Hz in octave steps. These levels coincide with the minimum requirements of current HPD testing standards. Subjects were then randomly assigned to one of the four HPDs and subsequently attended four experimental sessions separated by at least 24 hours. In each session, only one fitting procedure and one activity condition were used. Presentation order of the activity conditions was counterbalanced across the sessions, while the subject-fit conditions were always presented in the first two sessions to avoid a training effect.

All HPD attenuation data were collected using REAT procedures which required the subject to track his or her threshold under both occluded (HPD on) and unoccluded (HPD off) conditions. At each test frequency, the dB difference between the occluded and unoccluded thresholds was the attenuation of the HPD at that frequency. The tests were performed in a diffuse sound field within a sound-treated chamber, with test stimuli presented and responses scored via an IBM PC-controlled audio signal system, consisting primarily of Norwegian-Electronics 828 hardware. Each time an attenuation test was taken in the experimental sequence, separate thresholds were obtained for each of nine one-third-octave noise bands, with center frequencies of 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz, pulsed on-off at a rate of 2 Hz. The instrumentation and facilities for these tests, which meet the requirements of ANSI S12.6-1984, are discussed in detail in Casali (1988).

In each experimental session, the subject was first familiarized with the attenuation test and activity task procedures to be used and then given the first unoccluded test. If no temporary threshold shift from the screening audiogram was detected, the

session proceeded. The HPD was fit according to the assigned fitting condition, and once fit was established, the subject was not allowed to touch or adjust the HPD for the remainder of the 2-hour wearing period. Pre-task occluded thresholds were then obtained in the chamber, followed by the first of two periods on the assigned activity movement task in the workstation area. After a 5-minute break, the subject returned to the chamber for the second occluded threshold measurement, which occurred at 1 hour past initial fitting. Next, the second activity period was undertaken, followed by a short break and then the final post-task occluded threshold determination. At this juncture, the HPD had been worn for 2 hours without adjustment and attenuation data had been obtained after initial fit, after 1 hour, and again after 2 hours. Finally, the subject removed the HPD and the post-task unoccluded thresholds were obtained. User comfort data were also obtained before and after the task using psychometric rating scales; these results are the subject of Park and Casali (1990a), which is in Appendix I.

Laboratory Investigation Results

In data reduction, three attenuation values were computed for each of the 9 test frequencies: pre-task attenuation was the dB difference between pre-task occluded and unoccluded thresholds; post-task attenuation was the difference between post-task occluded and unoccluded thresholds; and, attenuation during the task (after 1 hour) was the difference between the second occluded thresholds and the mean of the pre-task and post-task unoccluded thresholds. There were no missing data points due to subject attrition or HPDs falling out of the ear. Although no HPDs worked completely loose, visible slippage occurred in approximately 20% of the subjects using the muff and in a few using the UltraFit earplug. Attenuation means and standard deviations for each HPD for all of the laboratory conditions appear in Table 1 (a through d).

The attenuation data set was first subjected to statistical analysis procedures aimed at determining if the "simulated" workplace factors had a degrading effect on the performance of the HPDs, and if so, was the effect specific to certain devices. Four-way mixed-factors analysis of variance (ANOVA) procedures were applied to the factorial data set; data for the dimensions of interest of the interactions found in the ANOVA were subsequently partitioned and subjected to simple-effects *F*-tests. Finally, for

Table 1-(a). Laboratory Attenuation Means (Standard Deviations) in dB for Each Experimental Condition for the E-A-R Foam Earplug.

E-A-R earplug: Attenuation means (standard deviations) in dB for each experimental condition at each measurement period.

Fit	Wearing Period Activity	Attenuation Measurement	1/3 - Octave Test Band Center Frequency (Hz)									
			125	250	500	1000	2000	3150	4000	6300	8000	
Subject Fit	Jaw Movement	AT1	20.7 (4.3)	22.5 (3.6)	23.5 (3.4)	25.4 (2.9)	32.4 (4.0)	39.7 (4.1)	38.8 (4.0)	44.4 (5.3)	40.1 (5.4)	
		AT2	20.4 (4.4)	21.5 (2.5)	22.9 (4.7)	24.5 (3.7)	32.8 (4.1)	39.1 (3.7)	38.4 (4.3)	43.5 (4.7)	39.4 (6.7)	
		AT3	20.4 (3.6)	20.8 (2.4)	22.7 (3.5)	24.7 (3.7)	31.7 (4.1)	38.7 (3.5)	38.3 (5.4)	42.9 (5.5)	39.8 (7.7)	
	Physical Work	AT1	19.5 (4.8)	21.9 (3.7)	23.7 (5.3)	25.5 (4.3)	32.5 (2.6)	37.5 (3.3)	39.7 (4.3)	43.2 (4.0)	40.2 (7.2)	
		AT2	19.5 (4.7)	21.8 (4.0)	23.9 (4.7)	25.9 (4.8)	32.8 (2.7)	37.5 (3.3)	39.6 (3.3)	43.2 (3.9)	39.9 (6.4)	
		AT3	20.0 (5.4)	21.4 (3.7)	23.3 (5.1)	25.7 (3.7)	32.8 (2.8)	38.8 (3.8)	38.5 (3.3)	42.3 (4.3)	39.0 (6.6)	
	Jaw Movement	AT1	32.2 (6.2)	35.3 (5.7)	37.3 (5.7)	39.7 (5.3)	35.0 (4.0)	41.9 (2.6)	43.2 (2.7)	45.7 (3.3)	44.4 (3.0)	
		AT2	32.1 (7.1)	35.8 (5.7)	37.2 (6.0)	39.7 (5.0)	36.0 (3.7)	41.0 (1.5)	42.0 (2.2)	45.5 (3.2)	44.4 (2.1)	
		AT3	31.9 (7.6)	34.4 (5.4)	37.1 (6.1)	39.2 (4.9)	35.9 (4.1)	41.6 (2.2)	42.5 (3.8)	45.4 (3.7)	43.8 (3.0)	
Physical Work	AT1	32.7 (7.8)	33.6 (6.6)	37.2 (5.5)	39.3 (5.1)	35.7 (4.1)	43.2 (3.0)	43.0 (3.8)	47.5 (4.4)	44.5 (3.9)		
	AT2	32.0 (7.2)	33.1 (6.8)	36.3 (4.6)	39.2 (4.9)	36.1 (3.9)	41.9 (2.9)	42.8 (3.5)	46.4 (4.2)	45.0 (2.8)		
	AT3	31.3 (7.3)	33.1 (6.0)	36.3 (3.8)	39.2 (4.7)	36.2 (5.1)	41.6 (2.4)	42.1 (1.9)	45.5 (4.2)	43.8 (2.7)		

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Table 1-(b). Laboratory Attenuation Means (Standard Deviations) in dB for Each Experimental Condition for the UltraFit Flanged Earplug.

UltraFit earplug: Attenuation means (standard deviations) in dB for each experimental condition at each measurement period.

Fa	Wearing Period Activity	Attenuation Measurement	1/3 - Octave Test Band Center Frequency (Hz)									
			125	250	500	1000	2000	3150	4000	6300	8000	
Subject: Fa	Jaw Movement	AT1	23.7(7.1)	22.6(8.8)	23.6(9.6)	22.8(8.2)	31.5(5.0)	35.0(6.2)	34.0(9.1)	38.8(12.1)	38.8(11.0)	
		AT2	19.2(7.9)	20.4(8.9)	21.2(8.8)	19.7(7.4)	28.4(5.1)	32.1(7.0)	31.9(9.2)	35.5(10.3)	36.8(10.3)	
		AT3	16.3(8.2)	18.4(9.2)	20.2(9.0)	18.8(7.1)	27.1(6.1)	31.1(8.3)	29.4(10.7)	32.8(10.3)	36.0(12.0)	
	Physical Work	AT1	23.7(7.9)	23.4(9.7)	24.6(10.1)	23.9(8.2)	31.5(4.8)	34.0(5.7)	34.4(7.1)	39.6(7.4)	40.1(7.9)	
		AT2	18.3(8.1)	20.9(9.0)	22.8(9.5)	21.4(8.6)	28.7(5.4)	32.5(6.6)	32.1(7.6)	36.4(8.8)	38.8(8.3)	
		AT3	18.5(8.7)	19.5(9.1)	21.7(9.1)	20.2(8.6)	27.2(5.9)	31.4(7.4)	30.9(7.2)	35.8(7.0)	37.3(9.4)	
	Jaw Movement	AT1	25.6(6.5)	26.8(8.1)	27.8(8.2)	27.8(9.1)	34.9(3.3)	37.2(5.5)	37.6(8.1)	40.0(7.5)	44.7(4.7)	
		AT2	23.7(7.1)	24.1(8.4)	25.5(7.8)	24.9(6.9)	32.7(2.9)	38.2(4.8)	35.8(7.0)	39.3(6.4)	42.9(5.2)	
		AT3	21.2(7.7)	23.0(6.9)	26.3(7.5)	23.3(6.7)	30.8(2.8)	36.7(5.2)	34.5(7.7)	38.0(8.2)	42.4(4.9)	
Trained: Fa	Physical Work	AT1	27.5(8.9)	27.5(8.6)	29.8(9.2)	29.1(9.2)	35.1(4.5)	37.8(8.4)	37.1(6.7)	40.7(7.1)	45.5(5.0)	
		AT2	24.3(7.3)	24.5(7.0)	27.8(8.0)	28.0(6.9)	33.3(3.6)	37.1(4.8)	38.0(6.3)	38.8(7.4)	43.6(5.7)	
		AT3	21.5(7.0)	23.8(8.3)	25.7(7.5)	23.3(6.3)	31.3(2.8)	35.8(4.5)	34.3(6.2)	37.8(6.7)	43.3(5.0)	

Table 1-(c). Laboratory Attenuation Means (Standard Deviations) in dB for Each Experimental Condition for the Bilson Earmuff.

Bilson UF-1 earmuff: Attenuation means (standard deviations) in dB for each experimental condition at each measurement period.

F#	Wearing Period Activity	Attenuation Measurement	1/3 - Octave Test Band Center Frequency (Hz)									
			125	250	500	1000	2000	3150	4000	6300	8000	
Subject F#	Jaw Movement	AT1	10.3(3.2)	14.4(2.7)	22.4(4.4)	28.8(3.9)	29.3(4.6)	36.1(4.6)	38.6(6.8)	43.0(7.3)	38.7(8.4)	
		AT2	9.3(2.4)	13.9(3.5)	20.2(2.8)	28.2(2.5)	28.8(4.5)	37.0(3.2)	39.1(4.6)	44.1(4.3)	38.7(3.7)	
		AT3	9.4(3.3)	13.9(2.4)	20.1(2.0)	27.6(3.0)	28.0(4.2)	36.6(2.4)	39.5(4.5)	42.2(4.8)	38.9(3.5)	
	Physical Work	AT1	9.6(3.7)	14.6(2.1)	20.2(3.6)	27.1(4.7)	28.5(6.2)	34.7(6.2)	36.9(5.7)	40.9(6.0)	37.1(7.5)	
		AT2	8.4(2.7)	12.2(3.3)	18.1(4.2)	25.7(8.9)	25.0(11.3)	33.0(10.5)	33.8(12.6)	37.1(13.8)	34.8(10.7)	
		AT3	8.3(4.9)	11.5(6.1)	17.4(6.1)	24.0(12.1)	24.0(13.0)	31.8(13.3)	32.4(15.0)	35.3(15.2)	31.9(13.0)	
	Jaw Movement	AT1	11.1(3.6)	15.9(3.3)	21.9(3.1)	29.5(3.0)	29.2(4.0)	37.8(4.7)	40.6(4.2)	41.4(4.7)	39.9(3.0)	
		AT2	9.8(2.2)	14.2(3.1)	20.7(2.9)	28.4(2.4)	29.1(3.0)	38.2(3.9)	38.3(3.0)	42.1(3.5)	38.2(3.2)	
		AT3	9.7(2.3)	13.2(2.8)	20.7(2.8)	27.8(2.2)	29.2(2.7)	38.8(3.0)	38.8(3.1)	41.8(3.3)	38.1(4.1)	
Physical Work	AT1	10.8(2.8)	15.9(3.7)	21.7(2.6)	28.5(3.6)	29.2(4.5)	37.5(4.2)	39.9(3.2)	39.6(5.2)	38.6(5.2)		
	AT2	8.7(2.1)	13.2(2.7)	21.1(2.9)	28.4(2.8)	27.9(3.4)	37.1(3.6)	38.5(3.5)	41.4(4.3)	38.4(3.0)		
	AT3	8.0(2.2)	13.5(3.2)	20.6(1.7)	28.4(3.2)	29.4(4.0)	37.5(3.1)	38.0(3.5)	40.4(4.3)	38.1(3.6)		

Table 1-(d). Laboratory Attenuation Means (Standard Deviations) in dB for Each Experimental Condition for the Bilsom Earmuff Worn over the E-A-R Foam Plug.

Bilsom earmuff over E-A-R earplug: Attenuation means (standard deviations) in dB for each experimental condition at each measurement period.

FH	Wearing Period Activity	Attenuation Measurement	1/3 - Octave Test Band Center Frequency (Hz)									
			125	250	500	1000	2000	3150	4000	6300	8000	
Subject FH	Jaw Movement	AT1	27.9(5.7)	32.9(5.2)	45.6(7.4)	45.0(7.1)	38.9(3.8)	47.2(4.4)	47.9(3.6)	50.1(4.3)	48.7(3.9)	
		AT2	25.2(5.7)	30.9(5.7)	41.9(7.1)	42.5(6.0)	36.6(3.1)	46.6(4.2)	47.2(3.2)	47.5(4.5)	47.0(3.9)	
		AT3	22.7(5.9)	28.9(5.8)	39.1(6.3)	40.1(5.4)	35.7(2.0)	45.6(3.6)	46.4(3.7)	47.3(4.7)	46.5(4.0)	
	Physical Work	AT1	25.7(6.6)	30.8(5.7)	41.6(7.2)	43.6(7.7)	38.4(4.3)	47.8(3.3)	48.3(3.8)	49.0(3.7)	48.5(3.0)	
		AT2	23.2(5.5)	28.2(6.1)	39.8(7.2)	42.0(7.4)	37.0(3.4)	46.3(4.2)	47.0(2.7)	47.0(4.5)	46.2(3.6)	
		AT3	20.7(5.5)	25.5(6.0)	35.8(9.2)	37.3(10.0)	35.3(6.0)	44.5(5.8)	45.8(4.6)	45.3(4.6)	44.5(4.5)	
	Trained FH	Jaw Movement	AT1	37.7(5.2)	43.6(5.6)	52.8(4.5)	49.1(4.7)	40.6(3.7)	48.2(4.9)	48.8(3.1)	50.5(4.0)	49.6(5.4)
			AT2	36.3(5.3)	42.7(5.4)	51.8(4.0)	47.9(3.5)	38.4(2.4)	46.8(3.8)	47.2(3.1)	49.5(3.9)	47.8(4.9)
			AT3	33.9(5.0)	41.9(5.6)	50.9(3.9)	48.9(4.3)	38.3(2.4)	45.5(3.4)	46.7(3.1)	48.2(4.2)	45.8(4.7)
Trained FH	Physical Work	AT1	38.1(6.1)	44.2(5.1)	55.2(3.6)	48.4(4.2)	39.7(3.1)	47.3(3.3)	47.8(3.5)	50.2(4.6)	50.2(4.8)	
		AT2	36.8(5.8)	42.6(5.2)	54.2(3.6)	46.5(4.2)	38.2(2.0)	45.6(3.0)	46.9(3.7)	48.6(4.3)	48.2(4.5)	
		AT3	34.0(5.7)	41.8(5.7)	53.8(4.2)	45.5(3.6)	36.7(2.4)	44.8(3.1)	46.3(3.7)	47.7(5.0)	47.4(4.5)	

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those factor dimensions with greater than 2 levels, the data were analyzed with post-hoc means comparisons tests, including Bonferroni-*t* and Newman-Keuls procedures, as appropriate (Keppel, 1982). All tests were conducted at $p < 0.05$ unless otherwise noted, and in all figures which follow, means with different letters are significantly different at $p < 0.05$. Details of the analysis procedures and computed test statistics appear in Casali and Park (1990) in Appendix I.

Fitting procedure effects. When subjects were trained to fit HPDs properly there was a significant increment in attenuation over that obtained with the use of package instructions alone. This was apparent in the 2 to 8 dB mean increases in spectral attenuation found in the fitting procedure main effect (Figure 1). The improvements were largest at 1000 Hz and below, and were significant at all frequencies except 6300 Hz.

More importantly, the effects of proper fitting instruction were found to be highly dependent on the particular HPD used. In reviewing the results for each HPD in Figure 2, it is evident that proper fitting substantially enhanced the protection afforded in each earplug condition, but not the earmuff. The improvements ranged from a low of 4.0 dB at 250 Hz for the UltraFit to a high of 14.1 dB at 1000 Hz for the E-A-R foam plug. These improvements were most pronounced at 1000 Hz and below. Negligible change between the two fitting conditions was found for the muff, which was quite straightforward to don. Of the two plugs in the sample, the user-molded foam plug was reported by subjects to be more difficult to insert properly than the premolded polymer plug, probably because of the need to roll, compress, and quickly insert it before it returned to its original shape. This was borne out by the larger low frequency (≤ 1000 Hz) attenuation differences (ranging from 11.9 to 14.1 dB) between subject-fit and trained-fit conditions than the corresponding low-frequencies differences (4.0 to 4.7 dB) for the polymer plug. The foam plug's sensitivity to user training was also evident in the plots for the combination protector, with the same pattern of influence at 1000 Hz and below as in the individual foam plug graph (Figure 2).

As a generic category of HPDs, earmuffs may be easier to don and less susceptible to the influence of user training than insert HPDs, as has been suggested in the results of previous studies (e.g., Casali and Epps, 1986; Casali and Lam, 1986). However, this is

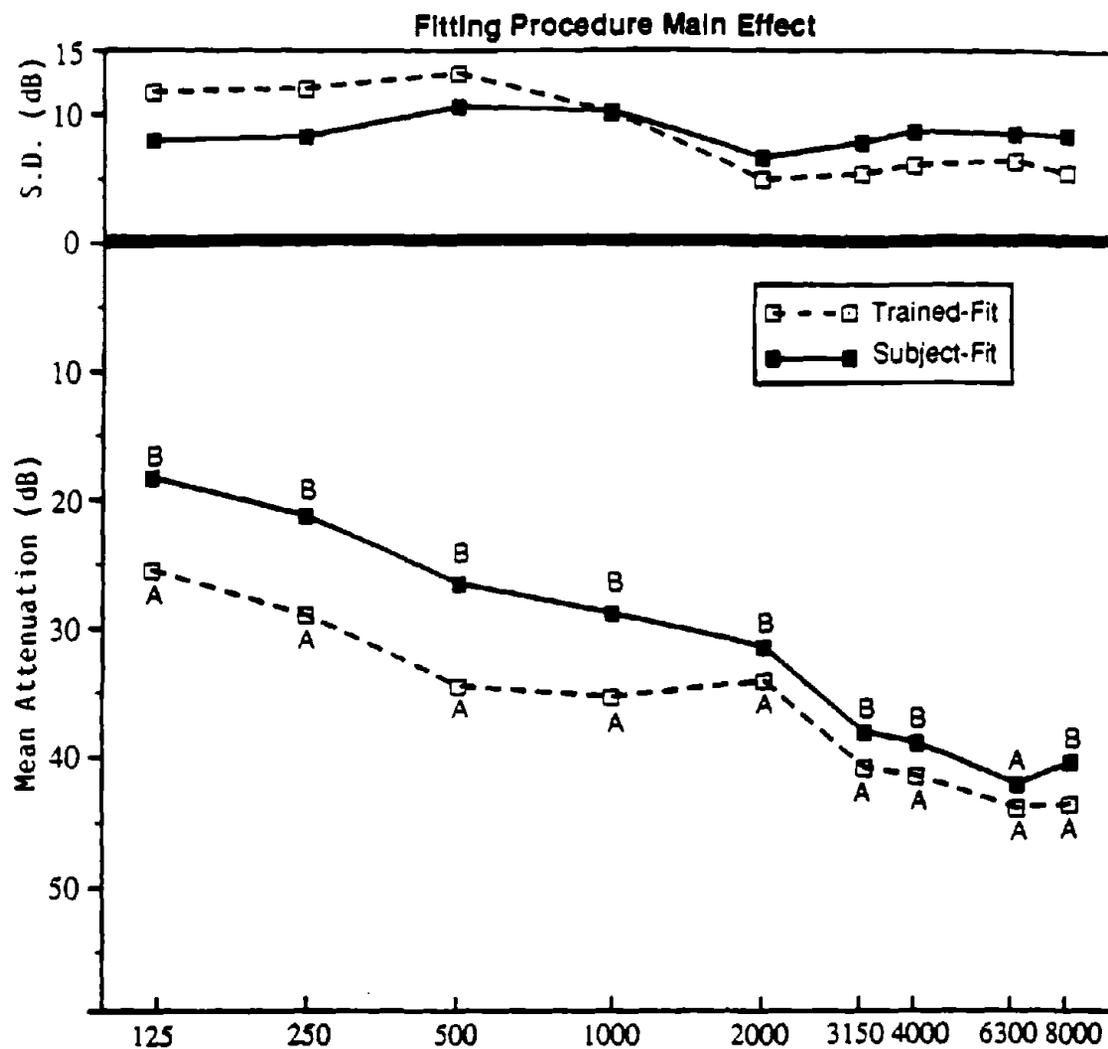


Figure 1. 1/3-OB laboratory attenuation (in dB) for each fitting procedure. (Means with different letters in each frequency column are significantly different at $p < 0.05$.)

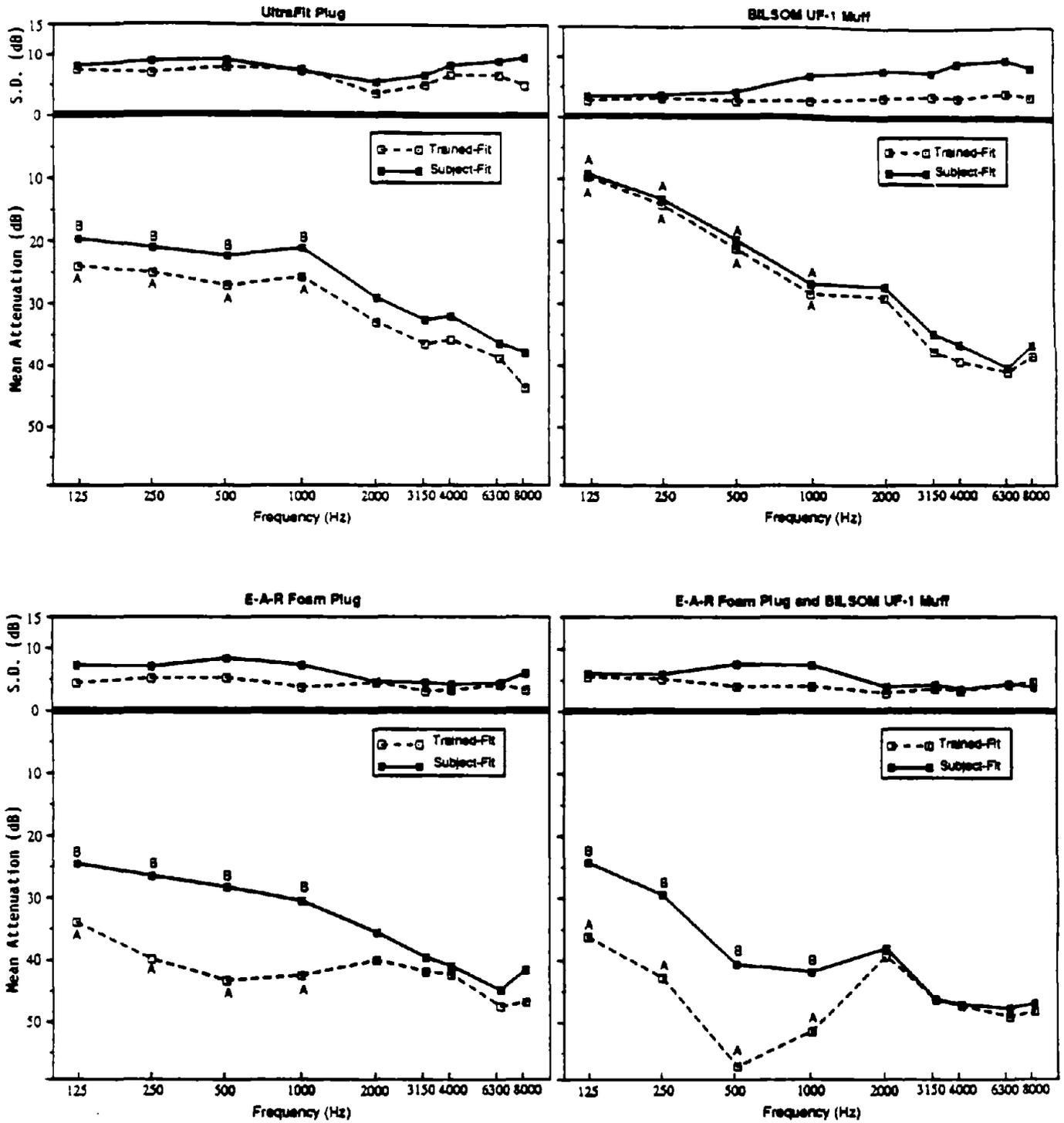


Figure 2. 1/3-OB laboratory attenuation (in dB) for each HPD and fitting procedure. (Means with different letters in each frequency column are significantly different at $p < 0.05$.)

probably not universally true for all varieties of muffs, some of which require fairly complex headband and earcup adjustments by the user. With most earplugs, it is especially important to pull the pinna of the ear upward and outward to straighten the ear canal prior to insertion. Lacking this, most individuals will obtain too shallow an insertion and a nonoptimal noise seal. It is questionable whether most workers practice such a technique when inserting plugs on the job; however, since laboratory attenuation tests for device NRR labeling purposes are aimed at optimal attenuation, this and other HPD placement aids are employed by experimenters. Thus, a portion of the discrepancy between advertised and field-achieved attenuation is attributable to the differences in fitting procedures. Furthermore, this effect may influence earplug's performance more than that of earmuffs, as suggested by these data.

An interaction of the fitting procedure variable with activity period time (as defined by the time juncture of attenuation measurement during the 2-hour period) suggested that the technique used in initial donning of the HPD affected the stability of the device over the wearing period. However, the effect was very slight and surfaced at only 500 and 6300 Hz (Figure 3), with a small mean reduction in attenuation from pre-task to post-task of 3.2 dB in the subject-fit condition compared to 1.5 dB in the trained-fit condition. Under both fitting conditions, the decrease in attenuation was monotonic across the three measurement junctures, pointing to the consistency of the activity period effect.

Activity movement and wearing time effects. Although there was a decrease in attenuation from pre-task to post-task, as evidenced by the main effect of the activity period shown in Figure 4, there were no discernable differences between the effects of the two types of activities during the period, i.e., heavy work-related movements or temporomandibular movements. The magnitude of the effect of the activity period on attenuation was largest for the UltraFit plug, followed by the muff/plug combination, the muff alone, and then the E-A-R foam plug which showed no loss in attenuation over the period (all shown in Figure 5). The average protection loss due to the 2-hour activity period was approximately 4 dB for the UltraFit. Not only was the performance of the muff resilient to fitting procedure effects, it also was only slightly affected by the activity. The pre-task to post-task attenuation losses were largest at 500 Hz and below, indicating the possibility

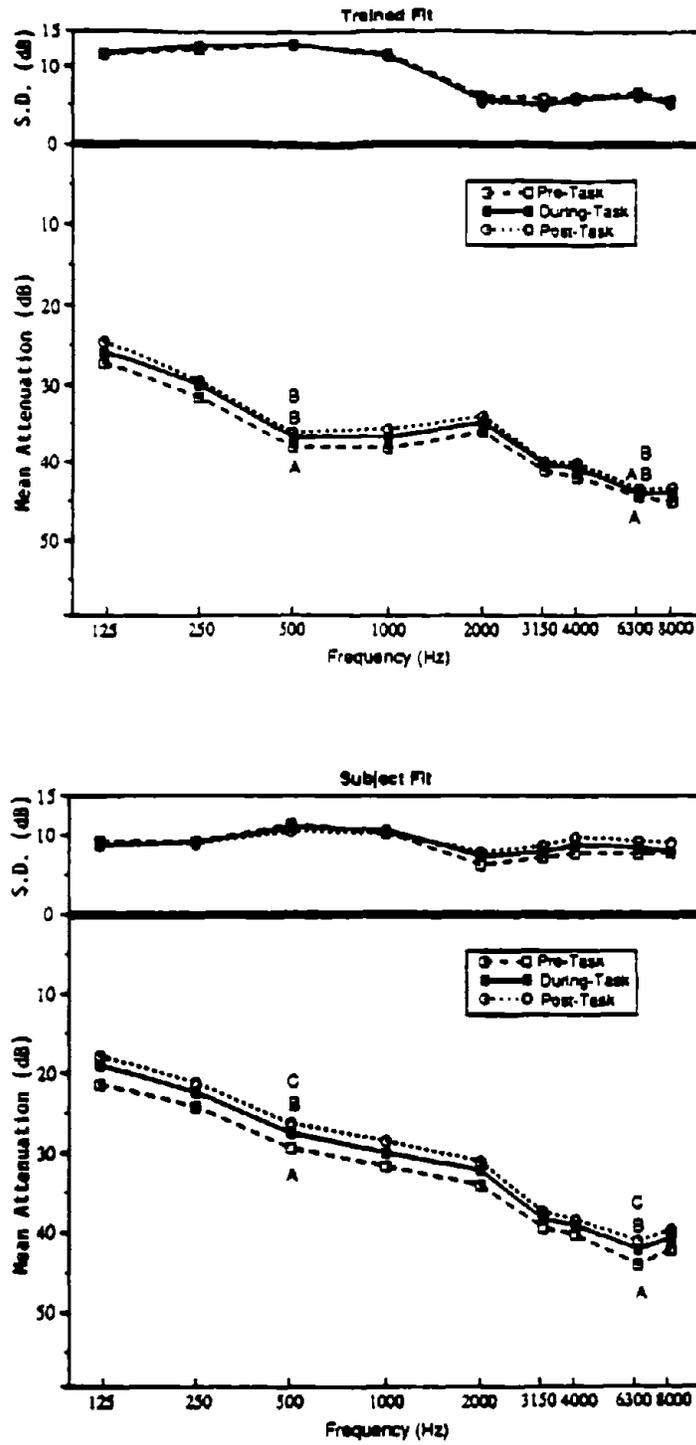


Figure 3. 1/3-OB laboratory attenuation (in dB) for each fitting procedure over the course of the activity period. (Means with different letters in each frequency column are significantly different at $p < 0.05$.)

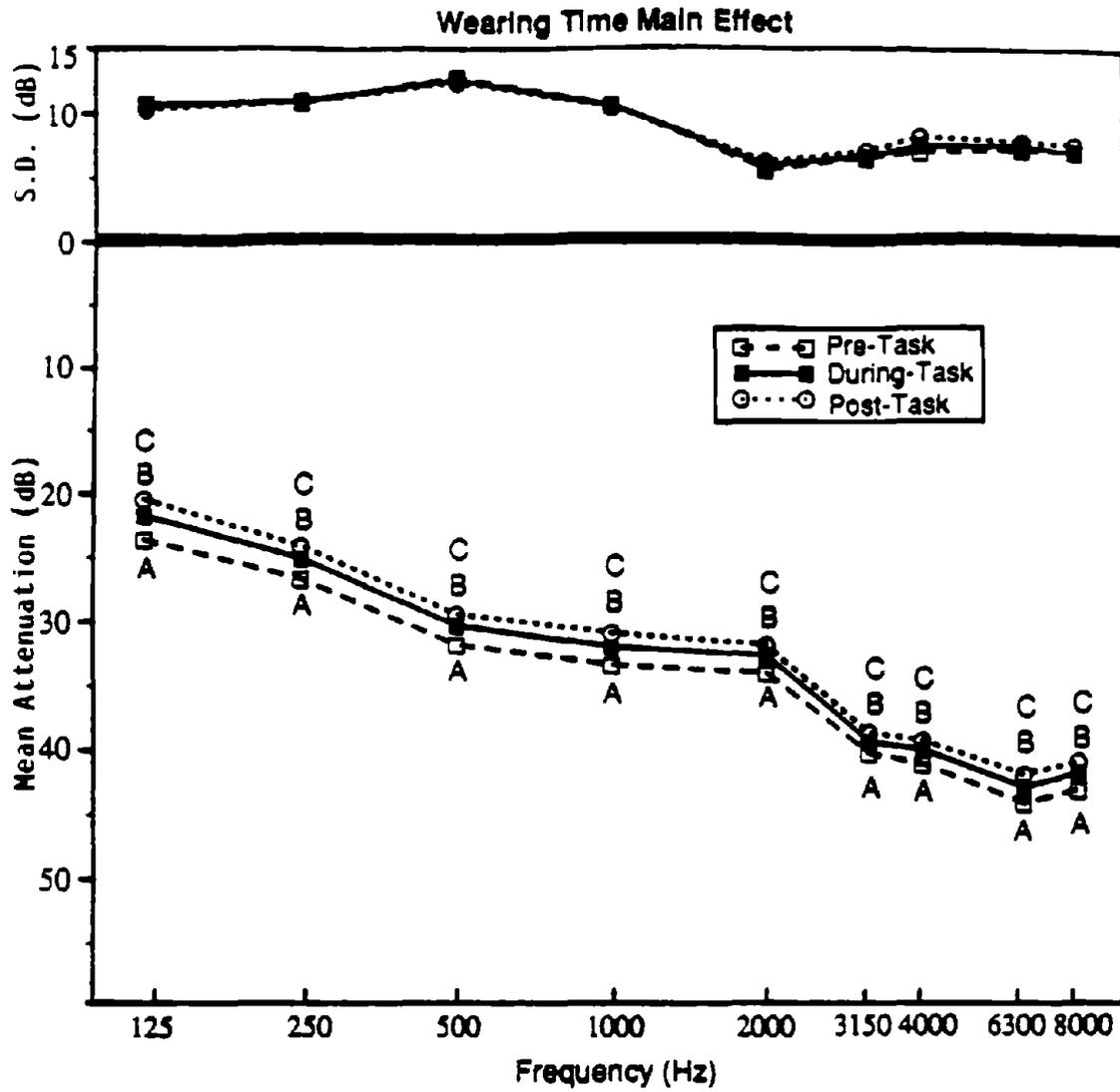


Figure 4. 1/3-OB laboratory attenuation (in dB) over the course of the activity period. (Means with different letters in each frequency column are significantly different at $p < 0.05$.)

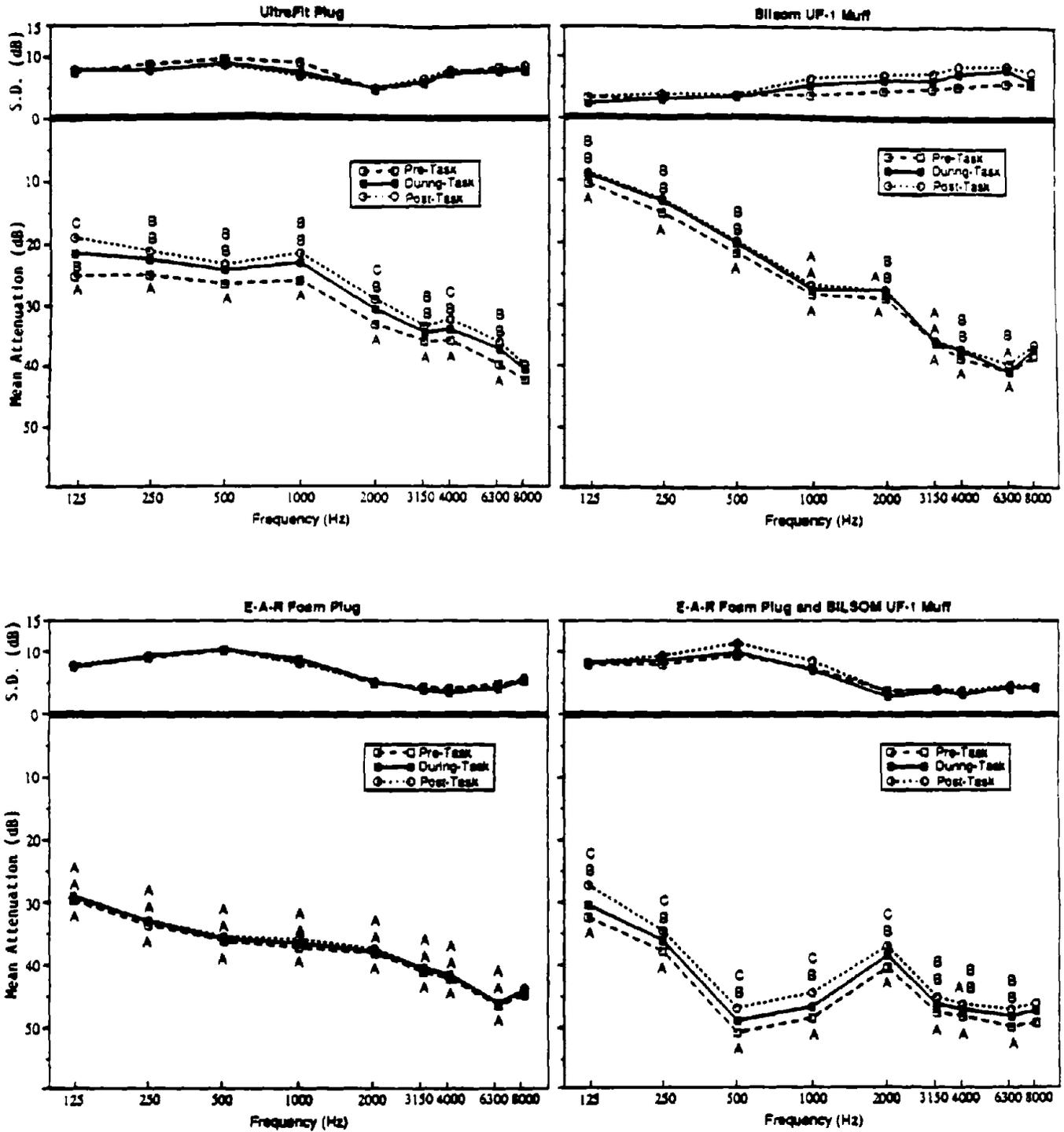


Figure 5. 1/3-OB laboratory attenuation (in dB) for each HPD over the course of the activity period. (Means with different letters in each frequency column are significantly different at $p < 0.05$.)

of loss of muff cushion seal, but were of minor practical significance (about 2 dB).

The tendency of the simulated activities to reduce protection levels provided by at least some HPDs suggests that work dynamics and user behaviors may compromise protection. However, the magnitudes of attenuation reduction produced by even these vigorous laboratory tasks were fairly small, which raises the question of whether the effects of the work can be adequately accounted for in a laboratory simulation. It is clear, however, that the laboratory protocol used in the study provides more realistic conditions for ascertaining HPD effectiveness than do the current standardized protocols, which utilize a stationary subject wearing a well-fit HPD for a very short wearing period.

INDUSTRIAL FIELD INVESTIGATION

Specific Aims

With the laboratory results in hand, the next step was to collect field data from actual industrial workers who use HPDs on a daily basis. The fundamental question remained as to how the laboratory results compared with attenuation achieved under actual field conditions. In this regard, a six-week field study served as a validation test for the laboratory simulation. In effect, since common HPDs, fitting conditions, and REAT (real-ear attenuation at threshold) procedures were used in both the laboratory and field studies, the resultant data sets could be used to assess the accuracy and feasibility of applying a laboratory simulation for estimating actual in-field HPD protection. This has important implications for designing new, intra- and inter-laboratory-repeatable HPD testing standards aimed at providing more realistic protection ratings.

Experimental Method

Design. Forty paid male volunteers, aged 20 to 59 years with mean of 37.9 and who were employees at the university working in noisy areas served as subjects. Each of the workplaces was within a mile of the test laboratory; therefore, the workers could be quickly retrieved for attenuation testing. The measured 8-hour time-weighted average noise levels for the various areas were:

Coal-fired power generating plant: 90.8 dBA
Printing-press shop: 88.5 dBA
Two metal-cutting machine shops: 87.8 and 86.5 dBA
Carpentry shop: 98.1 dBA
Airport: 106.4 dBA (during taxi activity only)

All workers were regular users of hearing protection on the job, but were intentionally chosen because of their unfamiliarity with the specific devices under study. Ten Workers were randomly assigned to one of four HPDs (E-A-R foam plug, UltraFit premolded plug, Bilsom UF-1 earmuff, or Willson Sound-Ban Model 20 canal cap) which they used at work for 6 weeks. The 2 earplugs and earmuff were the same HPDs as in the laboratory study. The Sound-Ban canal cap (NRR = 22) was added to the field study because some of the workers needed an intermittent use device; it was not included in the laboratory investigation because subjects complained of discomfort when wearing it continuously for the 2-hour task.

As in the laboratory study, HPD fitting procedure was a within-subjects variable consisting of the same subject-fit and trained-fit procedures described previously. During the first 3 weeks of their experience with the assigned HPD, subjects were told in an initial session to fit the device relying only on the manufacturer's instructions. Just prior to the second 3 weeks of the 6-week period, subjects attended a second fitting session where they were given the trained-fit procedures for donning the HPD.

Time period of use was also a within-subjects variable with three levels: week 1, 2, and 3. That is, subjects were retrieved from their work at unannounced times during each of the three weeks under each fitting condition (a total of 6 times) with their HPDs and attenuation-tested. This variable enabled the effects of practice and experience with the HPDs to be examined over a three weeks period.

Protocol. Subjects underwent 4 sessions for each fitting procedure condition, consisting of the HPD fitting session followed by 3 identical attenuation data collection sessions, with at least 5 days between data sessions. Audiometric screening was performed during the first fitting session, with the requirement that a hearing threshold level was 40 dB or less at any pure-tone test frequency in at least one ear and that the left/right threshold difference was 20 dB or less at a minimum of 6 out of the 7 test frequencies from 125

to 8000 Hz. After the initial session for either fitting condition, no further instructions were given for the ensuing three-week field usage period. Subjects were given replacement HPDs as needed.

The intent of the attenuation data collection sessions was to obtain realistic attenuation levels afforded by the HPD as it was fit and worn by the worker under job conditions. For this reason, subjects did not know when they would be greeted in their workplaces by an experimenter and requested to travel, via a five-minute car drive, to the laboratory for testing. A minimum of one week elapsed between tests on a single worker, and all tests were performed at least one hour following the start of a morning or after lunch shift. Once pulled from the workplace, the subject was not allowed to touch the HPD until after the occluded threshold tests. To preclude adjustment, the subject's hands were occupied during transit with a detailed set of instructions about the attenuation test, and once inside the test chamber, the subject was monitored via closed-circuit television. These procedures provided for the collection of realistic attenuation data under sound-field REAT protocol, which reflected actual protection achieved by the subjects using the HPDs on the job.

Upon arrival at the lab for each attenuation data collection session, the subject immediately entered the test chamber and was re-familiarized with and practiced in the threshold tracking procedures. Next, two occluded-ear trials were conducted at each of the nine test frequencies with the HPD fit as found in the workplace. Then the HPD was doffed and two unoccluded trials were obtained at each frequency. All instrumentation, calibration, and procedures for the attenuation test were identical to those used in the laboratory study discussed earlier. At the conclusion of each experimental session, the condition of the subject's HPD was checked and replaced if needed. The subject was then dismissed and driven back to work.

Field Investigation Results

Threshold data were reduced to attenuation scores by first calculating the dB differences between the first occluded and first unoccluded trials and between the second occluded and second unoccluded trials, and then taking the arithmetic mean for the two attenuation values at each frequency. The resultant data set for each experimental condition was complete as all 40 subjects attended all 6 data collection sessions. Attenuation means and standard deviations for all conditions appear in Table 2.

Analysis of variance (ANOVA) procedures were performed on the data for each test frequency to determine the effects of fitting procedure, time of use, HPD, and the interactions thereof on frequency-specific attenuation achieved in the workplace. Significant interaction effects included fitting procedure-by time of use-by HPD and fitting procedure-by-time of use at 2000 Hz and below, fitting procedure-by-HPD at all frequencies except 2000-4000 Hz, and time of use-by-HPD at the low frequencies of 125-500 Hz. Main effects were very consistent across across the spectrum and statistical significance included fitting procedure at all nine frequencies and HPD at all frequencies except 8000 Hz. 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 to isolate specific effects of interest and to conserve statistical power. Where appropriate, simple-effect *F*-test or simple-interaction effect *F*-tests were followed by pairwise means comparisons tests including Bonferroni-*t* and Newman-Keuls, as appropriate (Keppel, 1982). Unless otherwise noted, all tests were conducted at the $p < 0.05$ level and in all figures which follow, means with different letter or number labels are significantly different at the same probability level. Complete statistical tables for all tests appear in Park and Casali (1990b) in Appendix I.

Fitting procedure effects. As found in the laboratory study, the two fitting procedures produced markedly different attenuation results for the industrial subjects, at least for the insert-type devices. As shown in Figure 6 for the main effect of fitting procedure, the trained-fit condition provided 4 to 7 dB more attenuation, depending on frequency, than the subject-fit procedures. Also, consistently smaller standard deviations were

Table 2. Field Attenuation Means (Standard Deviations) in dB for Each Experimental Condition for Each HPD.

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)	19.7 (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)

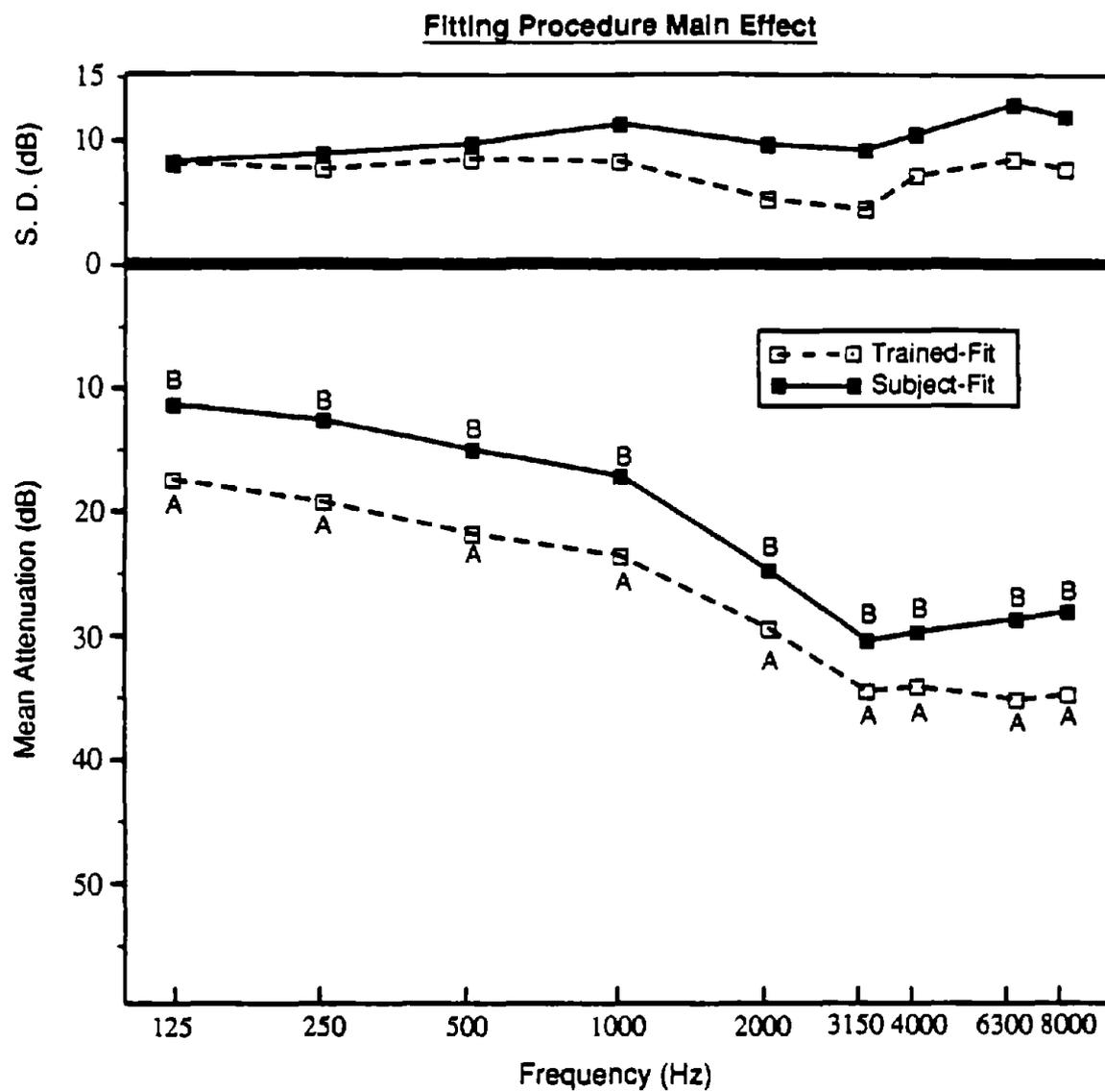


Figure 6. 1/3-OB field attenuation (in dB) for each fitting procedure. (Means with different letters in each frequency column are significantly different at $p < 0.05$.)

obtained in the trained-fit than in the subject-fit condition, attesting to the more uniform fit produced when training was used (Table 2).

The benefits of the trained-fit procedure were device-specific in that both earplugs improved in spectral attenuation over the subject-fit procedure, but the ear canal cap and earmuff showed only negligible (and statistically nonsignificant) effects (Figure 7). A particularly pronounced low frequency improvement surfaced with the user-molded foam plug, where proper training helped achieve a deeper insertion with fewer creases in the plug through which sound leakage can occur. On a frequency-dependent basis, the lowest and highest attenuation improvements due to training were 8.7 dB at 8000 Hz and 14.6 dB at 500 Hz for the foam plug, and 7.2 dB and 13.2 dB at 8000 Hz for the premolded UltraFit plug. The Sound-Ban canal cap also showed improvements of 1 to 4 dB across frequency with trained-fit procedures, but these differences were not significant at $p < 0.05$. Also, for all four devices, the attenuation standard deviations were smaller in the trained-fit than in the subject-fit condition, suggesting that a more consistent fit from person-to-person is likely to be achieved when proper fitting instruction is used.

Interaction effects of fitting procedure with time of use. It was discovered that the attenuation provided by the various HPDs tended to change over the course of the 3-week use period, and that this change was to some extent dependent on the fitting procedure used at the start of the period. Post-hoc tests on the fitting procedure-by-time of use interaction revealed a contrasting trend between the two fitting procedures: a slight protection loss (average reduction at ≤ 2000 Hz of 2.8 dB in attenuation over the 3-week period) occurred for the subject-fit condition; a slight protection gain (average spectral increase of 2.3 dB at ≤ 1000 Hz over the 3-week period) occurred for the trained-fit condition. These results are depicted in Figure 8. Again, the standard deviations for the trained-fit condition were consistently less than those for the subject-fit condition over the period of use in the workplace.

It should be noted that the interactive effect of fitting procedure over time of use did not hold for all HPDs, as indicated by the presence of the three-way interaction of these variables with HPD. Simple-effects *F*-tests on this interaction demonstrated that

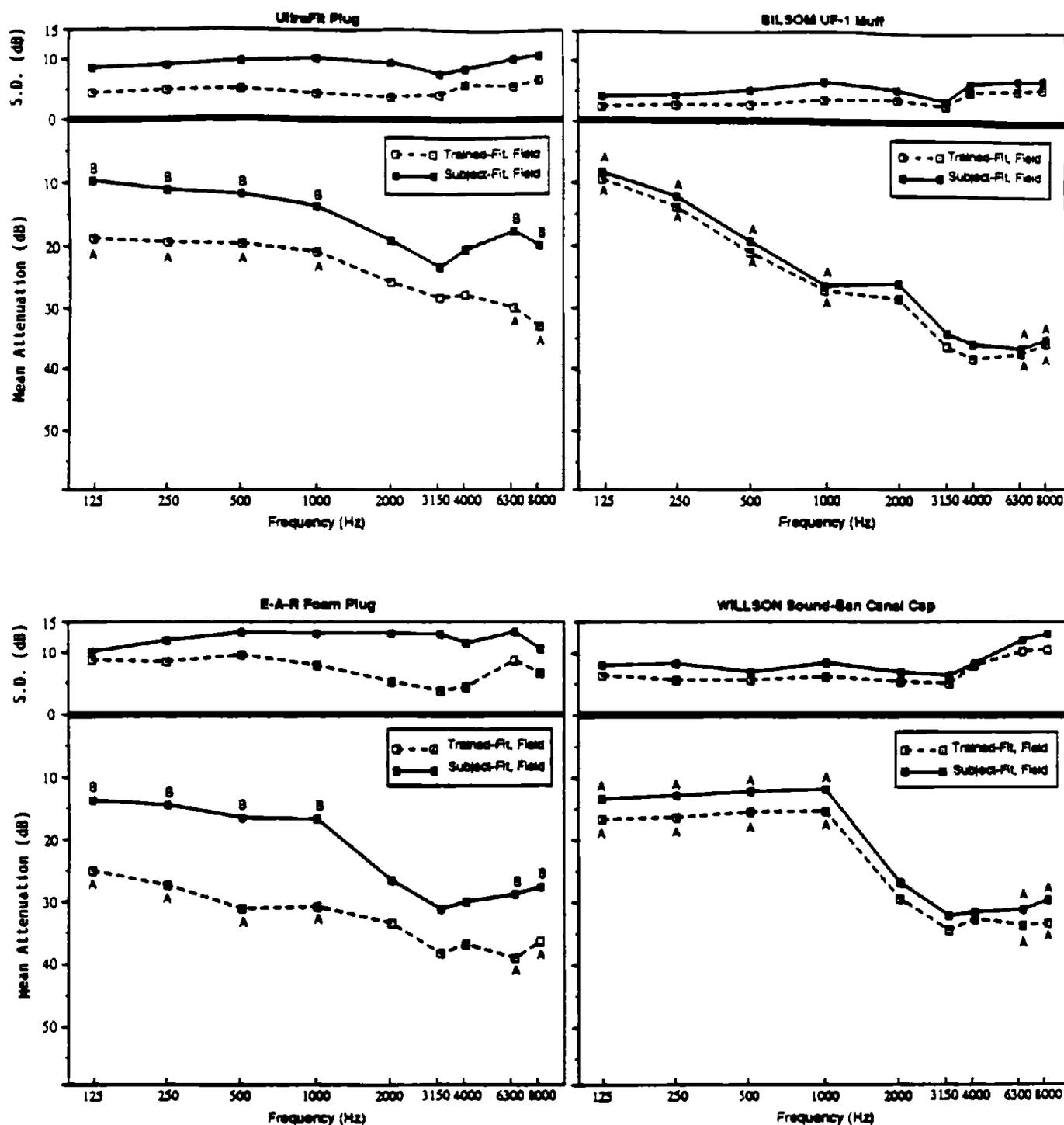


Figure 7. 1/3-OB field attenuation (in dB) for each HPD and fitting procedure. (Means with different letters in each frequency column are significantly different at $p < 0.05$.)

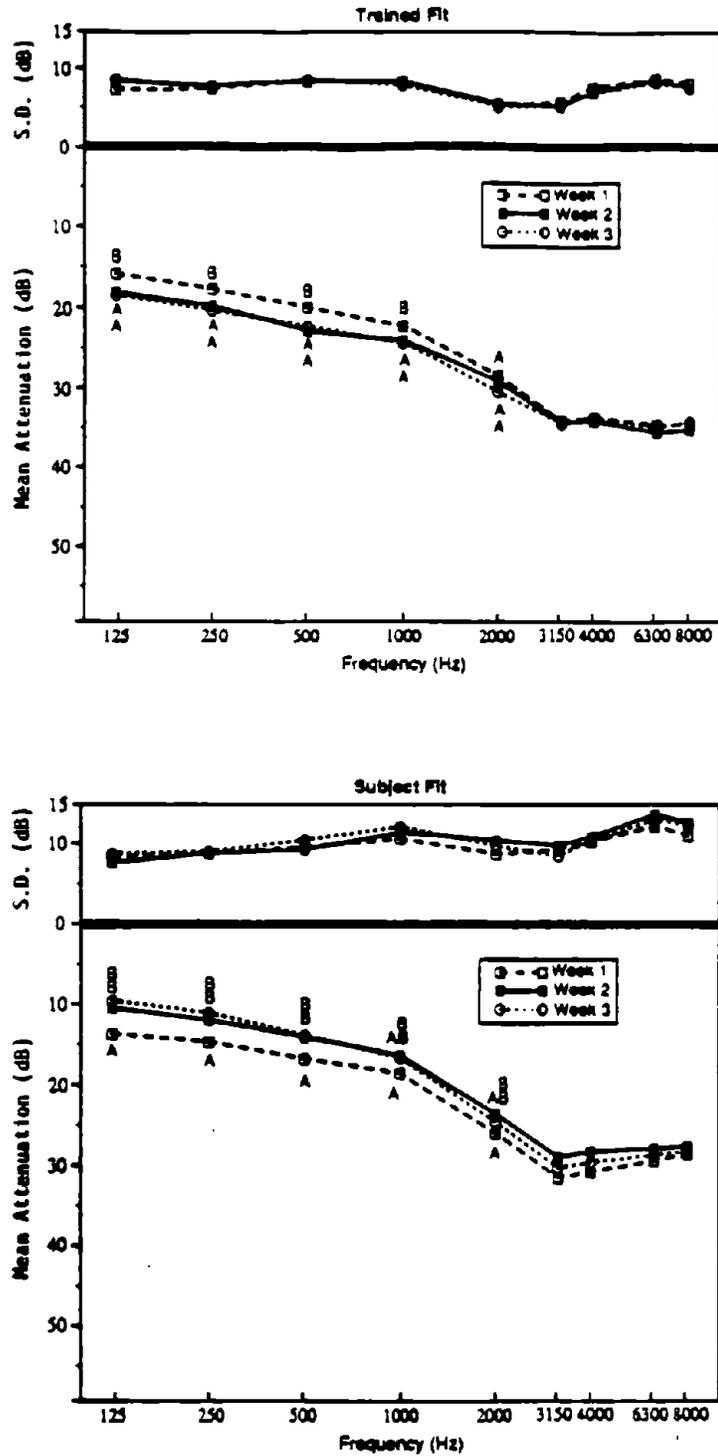


Figure 8. 1/3-OB field attenuation (in dB) over time under each fitting procedure. (Means with different letters in each frequency column are significantly different at $p < 0.05$.)

the fit-by-time effect was in evidence only for the two earplugs and that the attenuation of the earmuff and canal cap over the usage period did not change as a function of the initial fitting procedure used. The time effect on each earplug's attenuation achieved under each fitting condition is shown in Figure 9. When subjects were provided only with the manufacturer's package instructions for fitting, a gradual decrease in attenuation occurred with the UltraFit plug over the 3-week period. However, there was no significant reduction in protection afforded over the period when subjects were initially instructed with the trained-fit procedures. For the foam plug, the trend was somewhat different in that no significant attenuation decrease occurred between the first and third week with the subject-fit procedures, but attenuation did drop slightly after two weeks, followed by an increase back to initial attenuation levels in the third week. When this user-molded plug was fit according to the trained-fit protocol, an increase in protection of up to 6 dB occurred between the first and second weeks, and then the protection leveled off. One explanation for this trend is that some subjects are able to improve their placement of the foam plug with practice, but that this improvement may not occur unless proper training is initially provided on first use.

At the low frequencies of 125 - 500 Hz, there were changes in attenuation over the 3-week period when the data were collapsed across fitting procedure, but this effect was isolated to the UltraFit earplug, as discovered within the significant interaction of time of use-by-HPD. During the period, the average reduction in low frequency attenuation was 4 dB for the UltraFit plug, as depicted in Figure 10, and this effect was restricted to the subject-fit condition discussed earlier.

NRR data results. The EPA-required (EPA, 1985) Noise Reduction Rating (NRR) is currently the most common single-number rating reflecting broadband HPD attenuation across a frequency spectrum. In practice, the NRR is very important to manufacturers, buyers, and end-users of HPDs. Using the three sets of spectral attenuation data obtained from 10 subjects on each HPD (as per ANSI S12.6-1984 and EPA, 1985), NRR scores for each fitting condition were calculated. Besides the typical NRR (namely, NRR_{98}) scores with 2-standard deviation (SD) corrections, NRR_{84} values (with 1-SD corrections) were also calculated for more realistic estimation of real-world NRRs. The results are presented in Table 3, along with manufacturers' reported NRR values for comparison purposes.

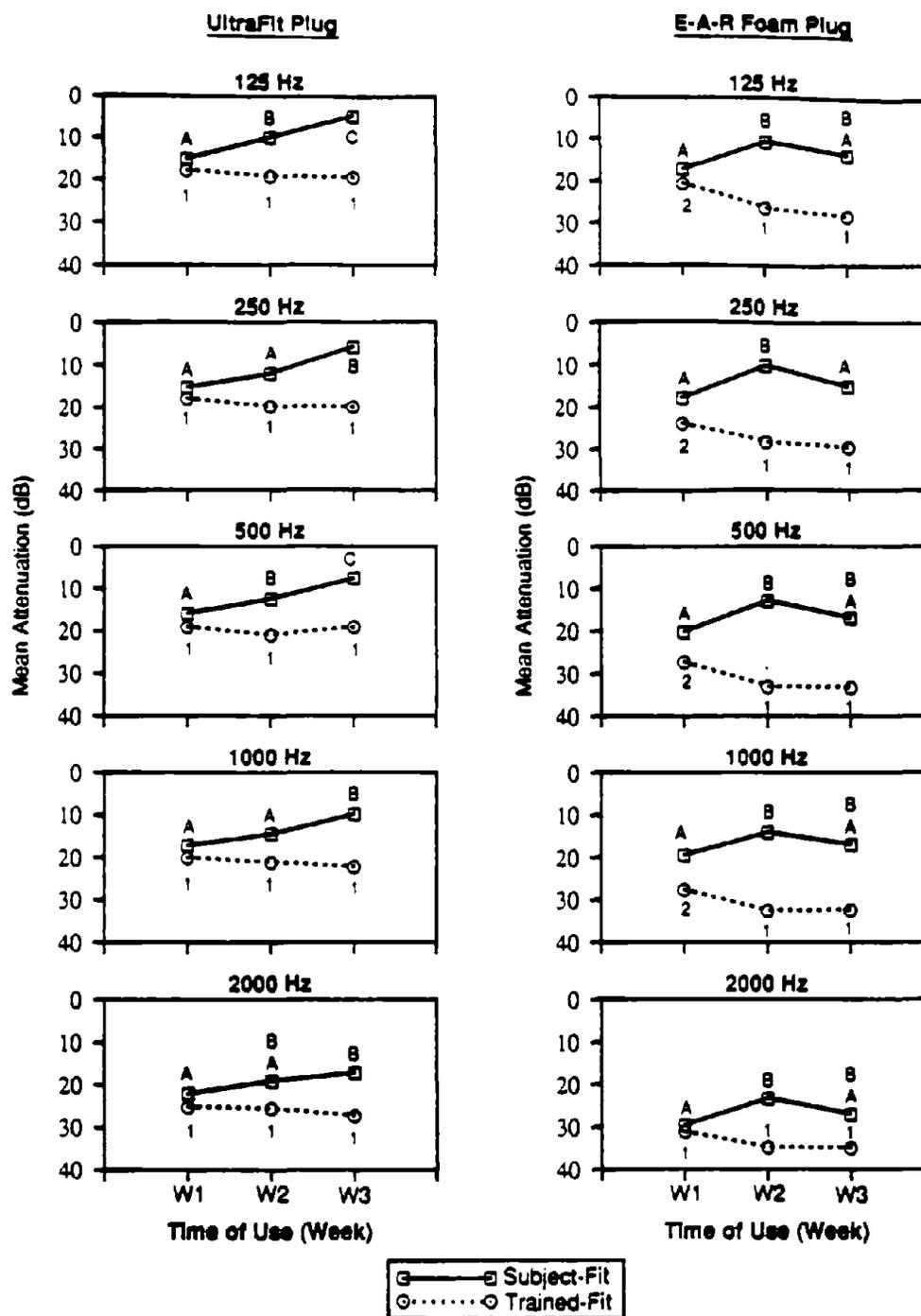


Figure 9. 1/3-OB field attenuation (in dB) over time under each fitting procedure for the UltraFit flanged and the E-A-R foam earplugs. (Means with different letters [for the subject-fit] or numbers [for the trained-fit] are significantly different at $p < 0.05$.)

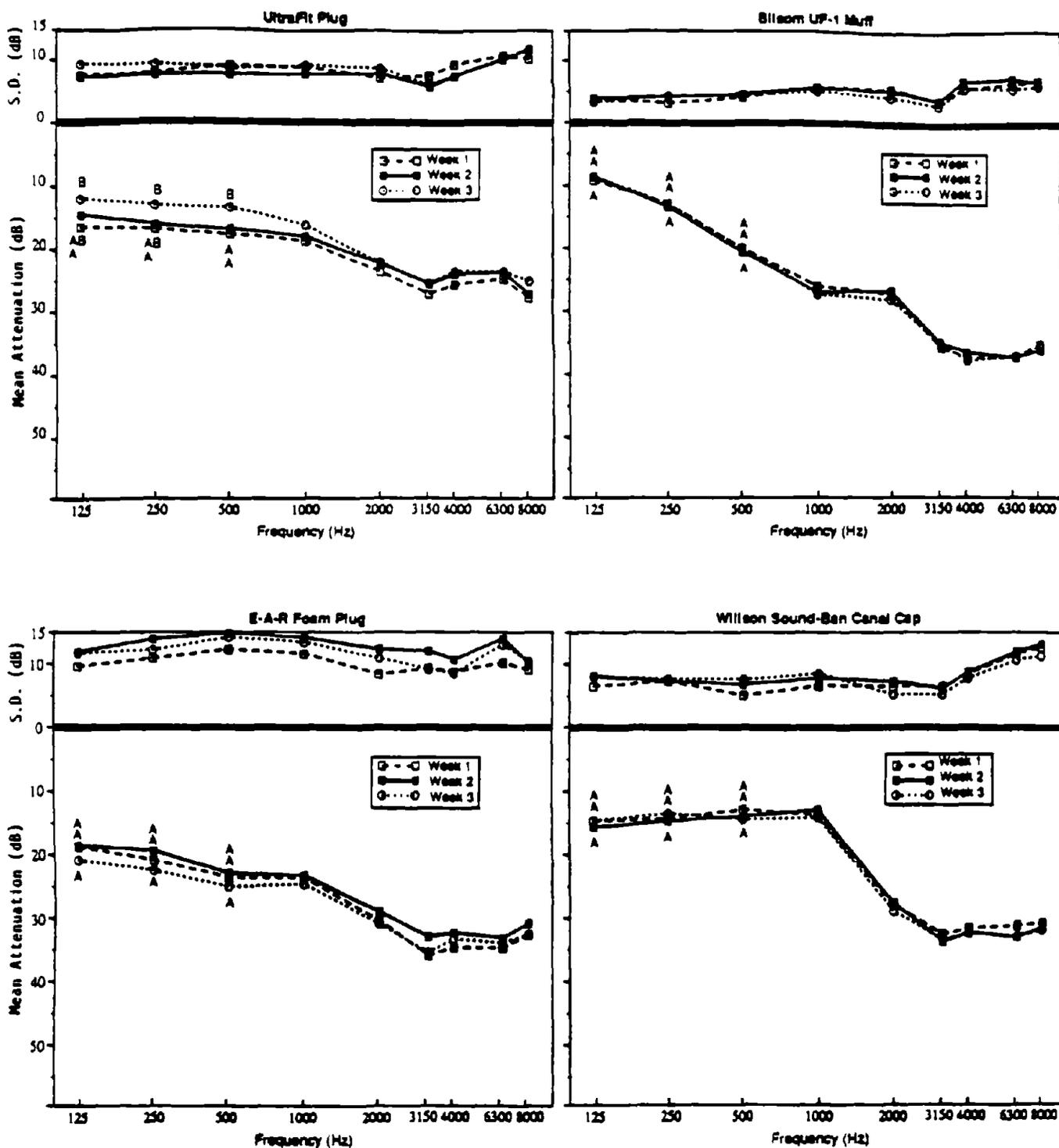


Figure 10. 1/3-OB field attenuation (in dB) for each HPD over time. (Means with different letters in each frequency column are significantly different at $p < 0.05$.)

Table 3. Field versus Manufacturer-reported NRR Scores (in dB)

	<u>Subject-Fit</u> <u>NRR₈₄¹</u>	<u>Trained-Fit</u> <u>NRR₈₄¹</u>	<u>Subject-Fit</u> <u>NRR²</u>	<u>Trained-Fit</u> <u>NRR²</u>	<u>Manufacturer's³</u> <u>NRR²</u>
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

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

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

³ Current manufacturer-reported NRR

As evidenced in both (NRR₈₄ and NRR₉₈) of the field NRR results, trained fitting (which yielded the highest field attenuation of any of the HPDs) provided substantially lower noise reduction values than the manufacturers' ratings: the discrepancy ranged from 6 to 10 dB (8 to 16 dB) when each of the field NRR₈₄ (field NRR₉₈) scores was compared with the manufacturers' NRRs. When subject-fit (perhaps the most realistic field condition) was used, overestimation of protection by the manufacturers' NRRs was worse: discrepancies of 9 to 23 dB (14 to 36 dB) resulted from the comparison with the field NRR₈₄ (field NRR₉₈) scores, respectively.

Prediction of field NRR using single 1/3-OB data. To estimate the HPD's overall field attenuation performance in a short and simple manner, it may not be necessary to have all spectral (i.e., 9-frequency) attenuation data. As suggested by a few researchers (e.g., Fleming, 1980; Padilla, 1976) and recently validated by Berger (1988), field attenuation measurements could be limited to only single test frequencies or single 1/3-OB test bands (i.e., centered at 500 Hz or 1000 Hz) to save considerable amounts of HPD testing time. If this approach is valid, individual workers' broadband protection levels could be ascertained quickly in the field by testing achieved attenuation at single frequencies. For this field study, the obtained 500 Hz attenuation data (namely AT500) were used for predicting broadband field protection, termed NRR_{PS} (NRR Per Subject). The NRR_{PS}, a modified NRR, is simply an NRR with no SD corrections, unlike the typical NRR (i.e., NRR₉₈) which incorporates a 2-SD correction. The NRR_{PS} was computed for each subject so that each observation in each experimental cell could have a one-to-one relationship with each 500 Hz attenuation data point.

For each HPD and each partitioned data set with respect to fitting procedures (i.e., overall, subject-fit, and trained-fit data), simple linear regression analyses were made of "NRR_{PS} on AT500." The resultant regression statistics (slope a , intercept b , and correlation coefficient r) are presented in Table 4; also, for obtained AT500 values of 10-30 dB, which represent the range of primary interest in the field, the differences between the measured AT500 values and the corresponding estimated NRR_{PS} values are presented in Table 5. Overall, the best prediction was accomplished by the UltraFit plug which provided the smallest mean difference (0.9 dB

Table 4. Single 1/3-OB Prediction of NRR_{ps} Regression Statistics Using 500 Hz Attenuation Data for Each HPD and Each Fitting Procedure.

REGRESSION	HPD ²	FIT	<i>a</i>	<i>b</i>	<i>r</i>
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 $NRR_{ps} = a \cdot AT500 + b$

Table 5. Differences Between the 500 Hz Attenuation Measurements and the Predicted NRRPs Values (in dB) for Each HPD and Each Fitting Procedure.

HPD ¹	FIT	Attenuation Measurement (in dB) at 500 Hz (AT500)					Average ²
		10	15	20	25	30	
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.

across the AT500 range of 10-30 dB) between the predicted (NRR_{PS}) and the predictor (AT500) values with $a = 0.89$, $b = 2.98$, and $r = 0.96$ (Table 5). For all HPDs, it is noteworthy that the subject-fit condition consistently provided better prediction performance than the trained-fit condition, based on differences in the values of slope, intercept, and correlation coefficient (Table 4) as well as mean differences between the predicted and the measured attenuation (Table 5). This fitting effect was particularly pronounced for both earplugs, supporting in part the significant fitting procedure effect for the earplugs found previously in the ANOVA results.

In addition, 95% prediction intervals (Myers, 1986) were constructed to estimate 95% probabilistic bounds within which single NRR_{PS} values were expected to fall, based on the given AT500 measurements. Using these prediction intervals (PIs), an individual's *minimum* field protection (i.e., NRR_{PS}) could be estimated, with 95% certainty, from a single 1/3-OB (i.e., centered at 500 Hz) attenuation measurement. For each HPD and each fitting procedure, the resulting PIs are illustrated in Figures 11 through 14. 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. When the 500 Hz data were collapsed across fitting conditions, the narrowest or "best" (an average of ± 3.1 dB across the 10-30 dB AT500 range) and the widest or "worst" (an average of ± 10.2 dB across the 10-30 dB AT500 range) predictions were obtained for the Bilsom muff and the E-A-R plug, respectively. When considering the separate data for each fitting procedure, the width of the PI was narrowest (an average of ± 2.8 dB across the 10-30 dB AT500 range) for the Bilsom muff under subject-fit and widest (an average of ± 12.8 dB across the same AT500 range) for the E-A-R plug under trained-fit. In general, the subject-fit data provided slightly more narrow PIs (i.e., better prediction performance for subject-fit NRR_{PS}) than did the trained-fit data for trained-fit NRR_{PS} , and this trend was especially pronounced for the E-A-R plug. Although the explanation of this discrepancy in prediction performance between the two fitting procedures (as evidenced in Tables 4 and 5 and Figures 11 through 14) is not clear-cut, it is practically very useful in that the subject-fit condition, which represents the most typical field fitting practices, provided noticeably better predictions of field NRR_{PS} values than the

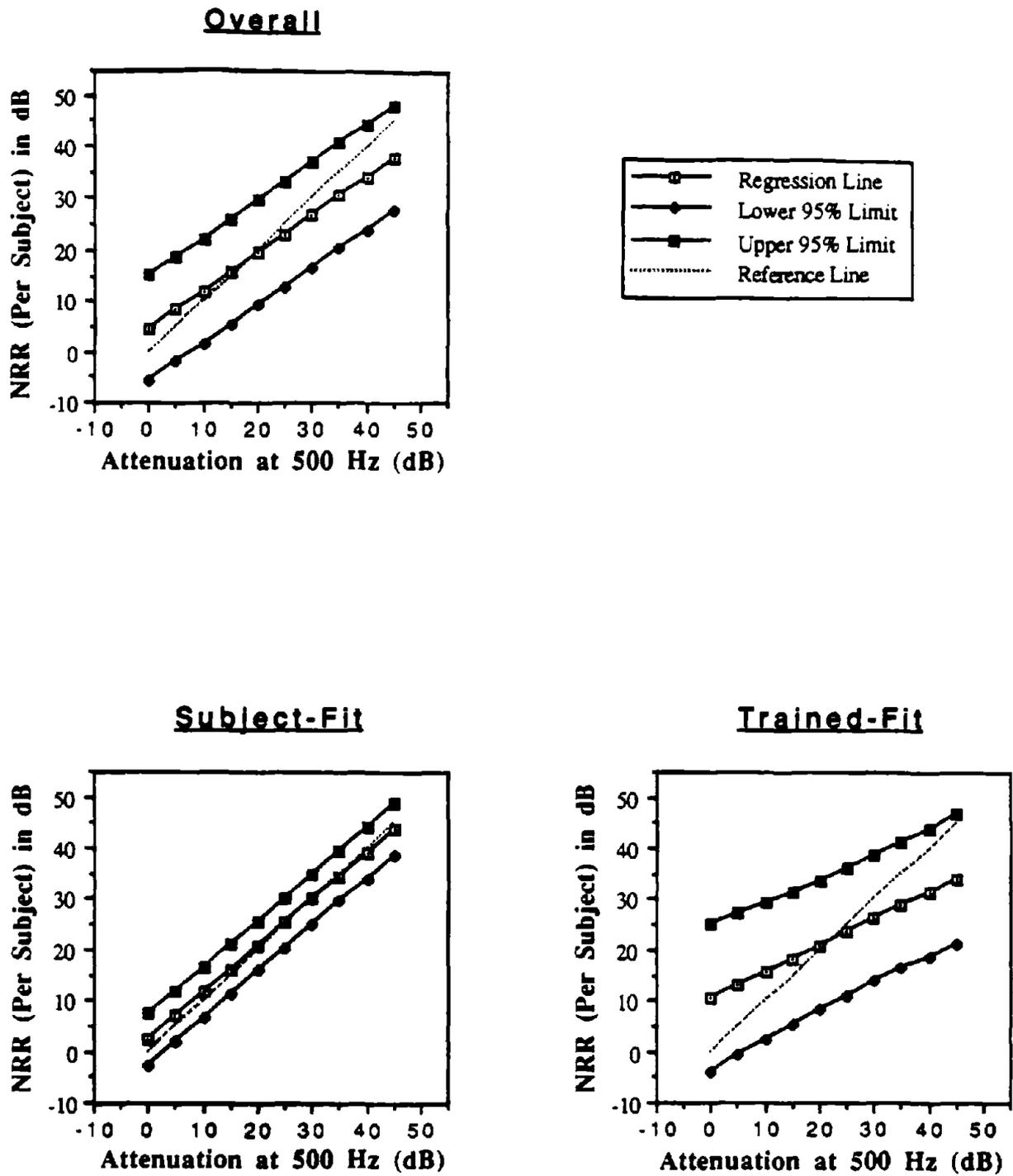


Figure 11. 95% prediction interval on NRR_{PS} (in dB) constructed from single 1/3-OB (500 Hz) attenuation data for the E-A-R foam earplug.

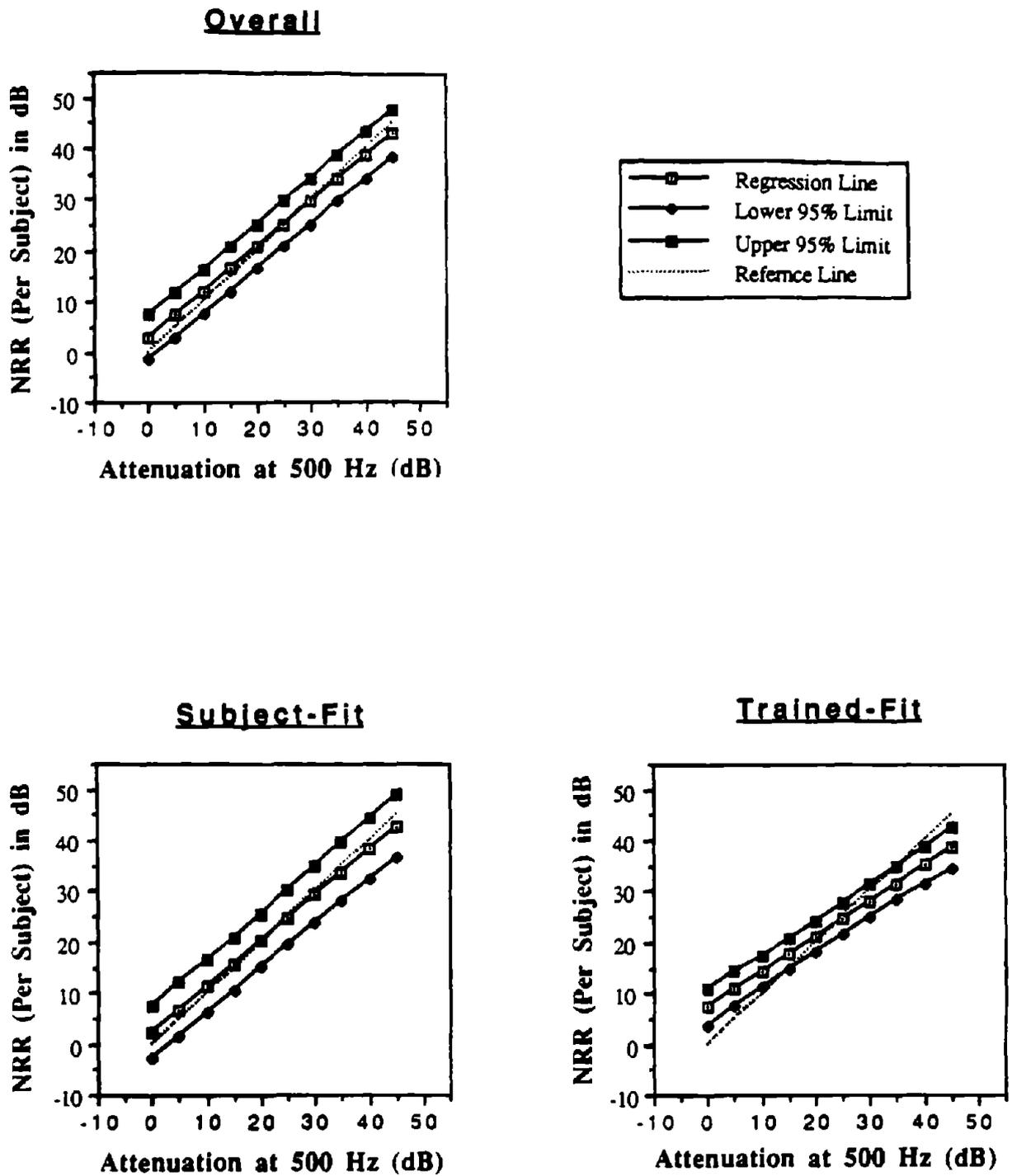


Figure 12. 95% prediction interval on NRR_{ps} (in dB) constructed from single 1/3-OB (500 Hz) attenuation data for the UltraFit flanged earplug.

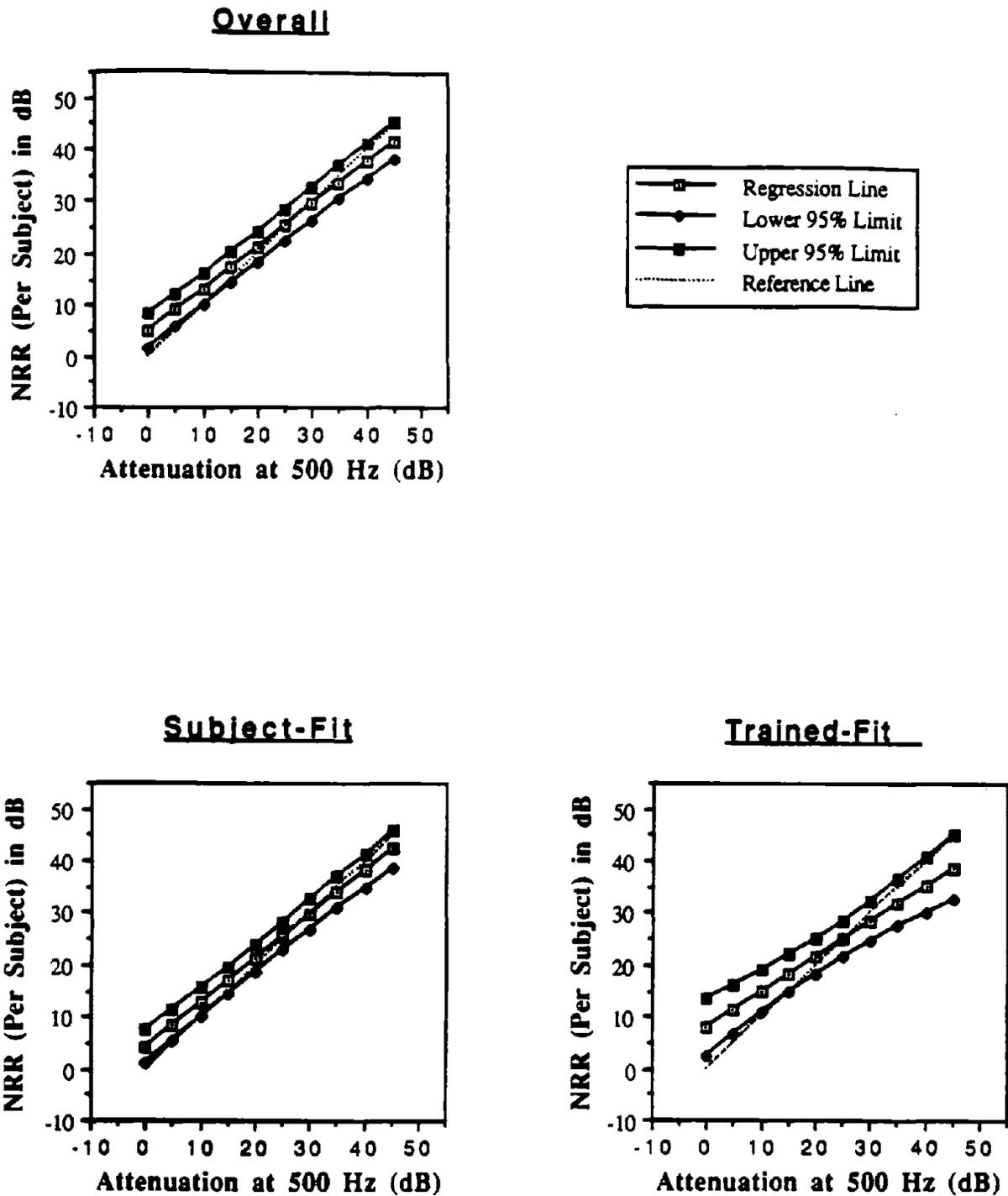


Figure 13. 95% prediction interval on NRR_{PS} (in dB) constructed from single 1/3-OB (500 Hz) attenuation data for the Bilsom earmuff.

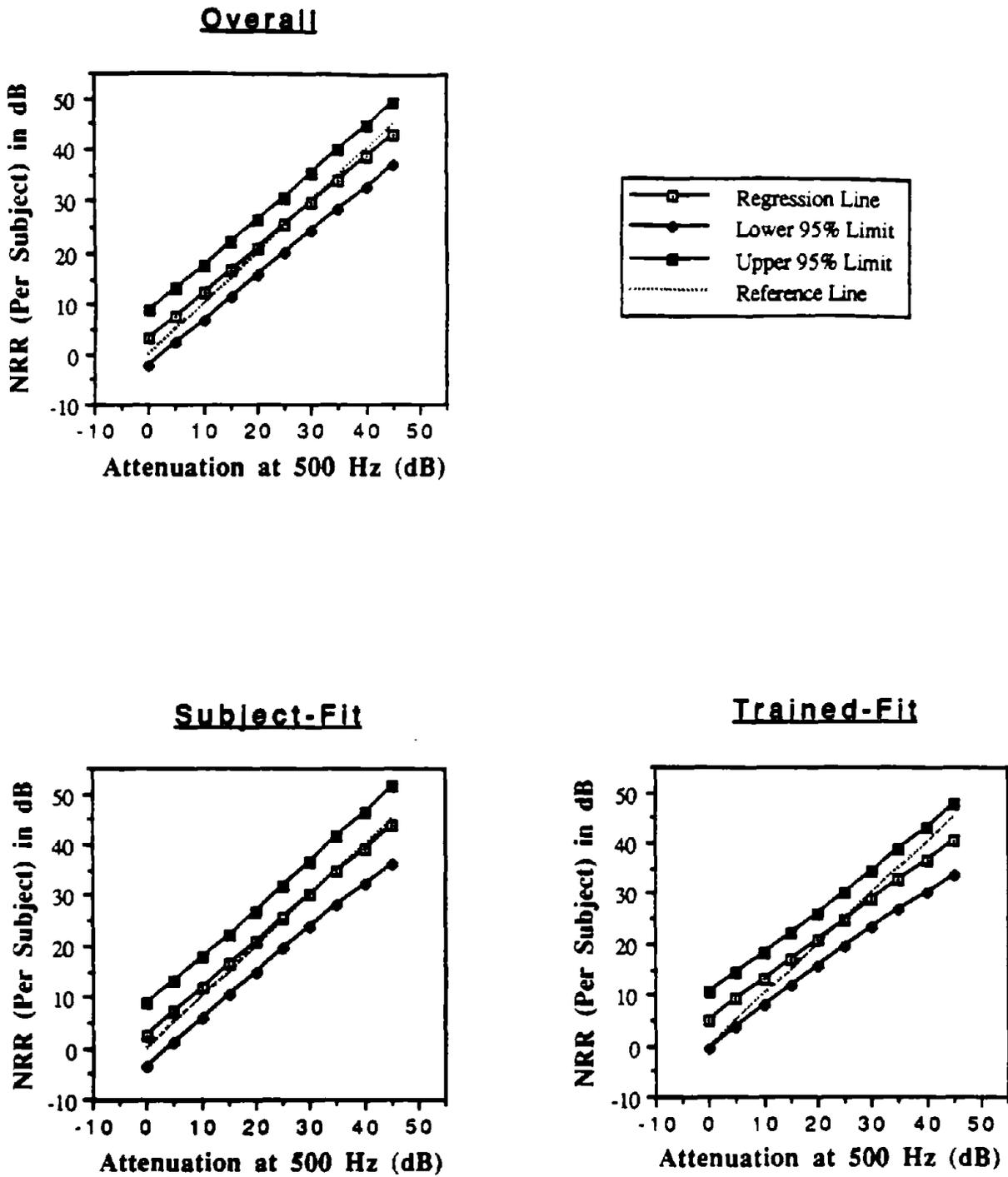


Figure 14. 95% prediction interval on NRR_{ps} (in dB) constructed from single 1/3-OB (500 Hz) attenuation data for the Willson canal cap.

trained-fit condition. In other words, since all HPDs when placed by the subjects yielded very good prediction results, it appears that the 500 Hz data may be useful in obtaining estimates of broadband spectral protection for individual workers in industrial conditions.

CONTRAST OF LABORATORY VERSUS FIELD STUDY RESULTS

A fundamental objective of this research project was to obtain two sets of attenuation data, one from a highly-controlled laboratory protocol and one from an industrial setting, for a common set of popular HPDs worn under similar fitting conditions and tested under common REAT test procedures in each setting. Meeting this objective enabled direct comparisons to be made between the laboratory and field data. A central issue related to the formal, standardized testing of hearing protectors for labeling purposes was how well the attenuation data yielded by the laboratory protocol corresponded to that obtained under actual workplace conditions. To examine this issue, statistical comparisons of the results from the two settings were made.

For each of the three HPDs common to both studies (E-A-R foam plug, Bilsom UF-1 muff, and UltraFit premolded plug), pairwise comparisons, selected on an a priori basis, were made among four sets of attenuation data resulting from the two fitting procedures (i.e., by collapsing across other factors) 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 sets. Two-sample *t*-tests were applied for comparisons of the LS-FS, LS-FT, LT-FT, and LT-FS pairs, while paired *t*-tests were appropriate for comparisons of the LS-LT and FS-FT pairs. All six *t*-tests were performed in each of two comparison situations with different sets of laboratory data: (1) pre-task laboratory (i.e., just after initial fit and preceding work activity tasks and HPD wearing period) and (2) post-task laboratory data (i.e., following two hours of HPD wearing time and the activity tasks).

Comparisons Using the Pre-Task Laboratory Data

The pre-task laboratory condition most closely corresponded to that used in current ANSI HPD attenuation test protocols (ANSI S3.19-1974; ANSI S12.6-1984), that is, a test of protector performance for a just-fit subject who is seated motionless during the test procedures. The important question was how much the field

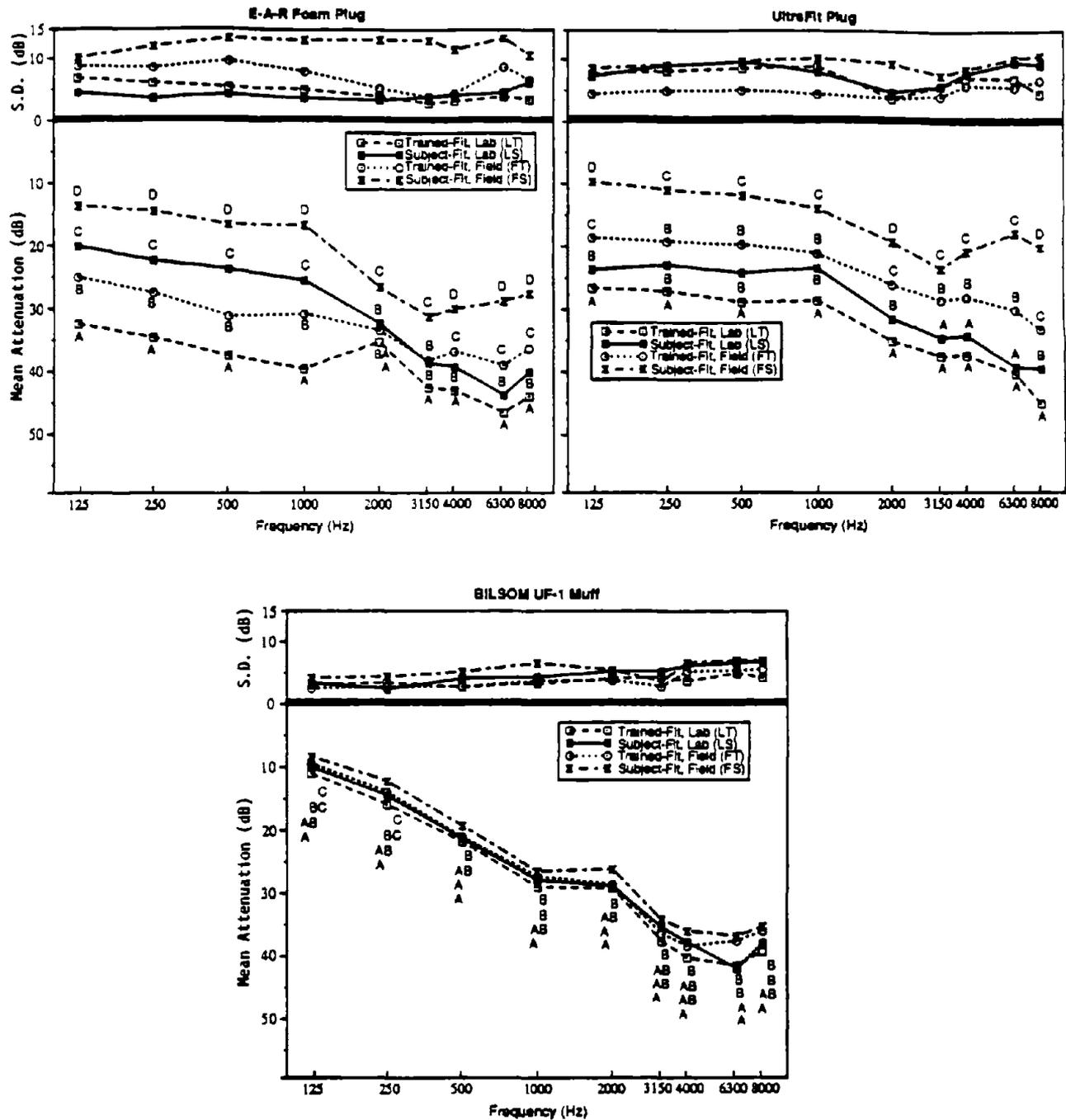
and laboratory data differed when the laboratory data was obtained immediately after HPD fitting, before the subject underwent the vigorous movement task.

According to the *t*-test comparison results (Figure 15), both earplugs showed consistently significant differences between the laboratory and field at all frequencies except 2000 Hz, as demonstrated in the LS-FS and LT-FT pair comparisons. The foam plug displayed an average attenuation advantage (across frequency) of 8.9 dB and 6.4 dB for the laboratory protocol over the field protocol in the subject- and the trained-fit conditions, respectively. For frequencies below 2000 Hz, the LS results underestimated the FT values for the foam plug. On the other hand, the UltraFit plug showed greater mean differences between the laboratory and field than the foam plug: mean differences of 13 dB across frequency for the subject-fit and 9 dB for the trained-fit. Also, this premolded plug achieved significantly more attenuation in the LS condition than in the FT procedure over frequencies of 125 and 2000-8000 Hz. In essence, none of the laboratory conditions yielded reasonable estimates of field attenuation performance for either insert device.

On the other hand, the earmuff showed less pronounced differences between the laboratory and field tests than the earplugs: no significant differences were found at 1000, 3150, 4000, and 8000 Hz for the LS-FS comparison, and at 500, 2000, 3150, and 4000 Hz for the LT-FT contrast. The mean attenuation differences between the two protocols were small: 2.3 dB and 1.8 dB for the subject- and the trained-fit conditions, respectively. For the earmuff, the subject-fit laboratory condition provided very similar mean and standard deviation values to those obtained under trained-fit in the field, thus yielding a good prediction of actual protection afforded.

Comparisons Using the Post-Task Laboratory Data

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 two-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 the field study herein. The post-task laboratory data consistently yielded lower attenuation than the pre-task data, except for the foam earplug.



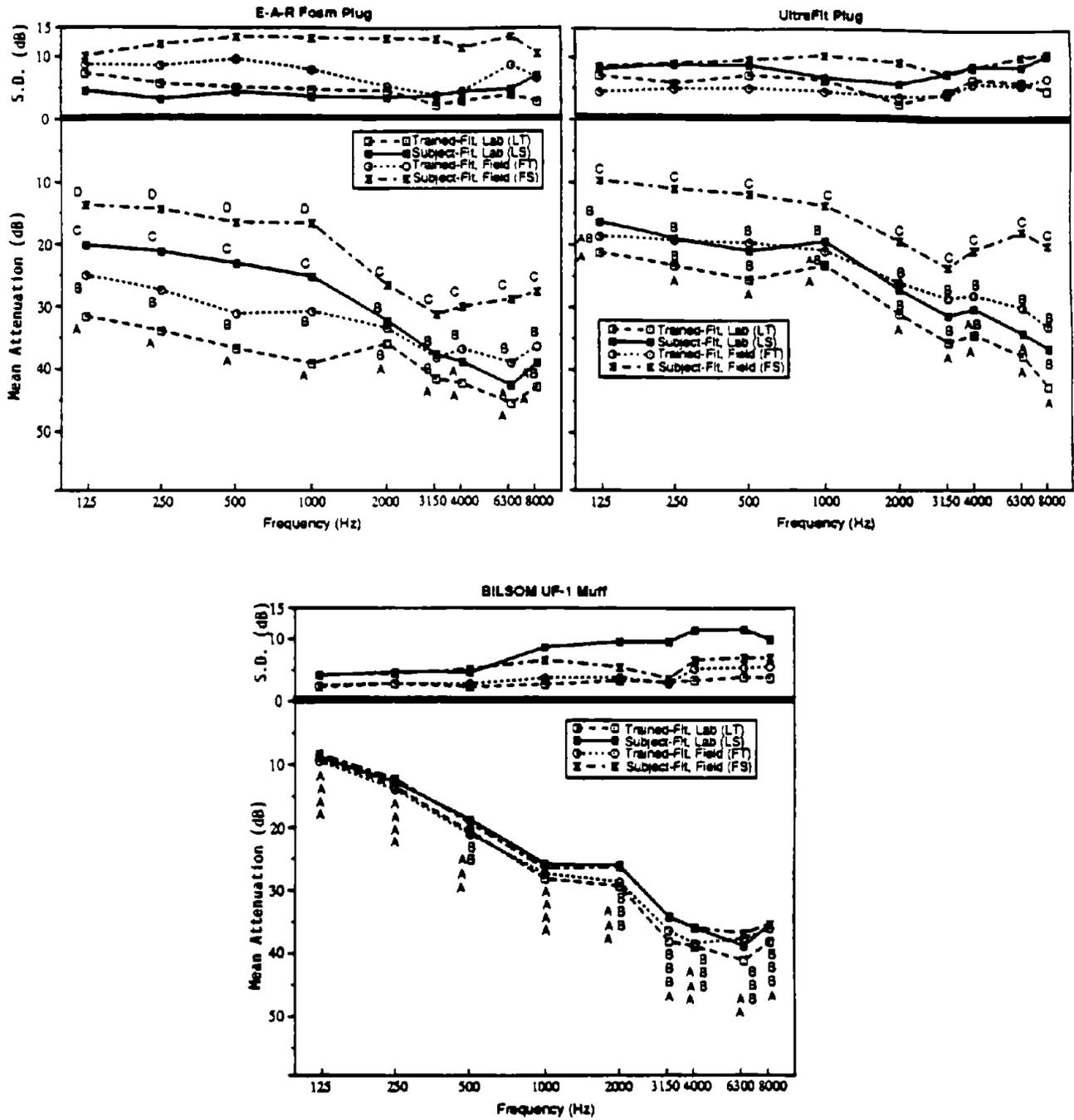
* Lab Data: Using Mean of Pre-Task Observations
 Field Data: Using Mean of 3 Weekly Observations

Figure 15. 1/3-OB attenuation comparisons of field data with pre-task laboratory simulation data. (Means with different letters in each frequency column are significantly different at $p < 0.05$.)

Based on the comparison results depicted in Figure 16, the foam plug exhibited very similar post-task comparison results to those obtained previously with the pre-task laboratory data (i.e., no significant pre- to post-task attenuation reduction), even after two hours of wearing time while undergoing vigorous activities. This was because once fit, the foam plug tended to remain stable in the ear canal in the laboratory study. However, the results of the LS-FS and LT-FT comparisons clearly indicated that field and post-task laboratory data were significantly 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 for the foam plug. The closest approximation of the best field performance (i.e., the FT results) was provided by the LS data, though the attenuation values produced under LS were up to 9 dB lower than than the FT values at the lower frequencies. Clearly, the laboratory results did not offer accurate predictions of actual attenuation achieved in the workplace by the foam plug users.

For the UltraFit plug (Figure 16), the comparison results were similar to those of the foam plug, but the laboratory versus field differences were less pronounced. Even after two hours of movement activities, attenuation obtained in the laboratory protocol was noticeably higher than that achieved in the field, by an average of 10 dB and 6 dB for the subject-fit and the trained-fit conditions, respectively. However, the LS data did provide reasonable agreement with the FT results at most frequencies.

In the case of the earmuff, laboratory and 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 (Figure 16). The differences across frequency were less pronounced than those found in the previous comparison with the pre-task laboratory data, corresponding to the fact 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.



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

Figure 16. 1/3-OB attenuation comparisons of field data with post-task laboratory simulation data. (Means with different letters in each frequency column are significantly different at $p < 0.05$.)

Overall, from the results of the attenuation data contrasts, it can be concluded that attenuation obtained in the laboratory did not closely represent actual field attenuation, except for the earmuff.

DISCUSSION

Both the laboratory and field studies clearly showed that training workers to properly fit HPDs is critical to achieving adequate attenuation performance, particularly with insert HPDs. When the workers rely solely on manufacturers' package instructions to don HPDs, they often fit them improperly and/or incompletely. This may be because manufacturers' on-package instructions are often (and sometimes, necessarily) brief, hard to read, and limited in content due to the small printing space available. Of course, some individuals will miss or disregard even the best instructions and fit the HPD as they wish. But it is evident that comprehensive, easy-to-understand, and field-usable instructions for each hearing protector constitute a helpful step toward enhancing protection. After all, training is an essential part of a successful industrial hearing conservation program. Motivational strategies should also be implemented along with the training.

Since the field data provided attenuation far below the levels reported by manufacturers on package labels, 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. A reasonable "ball park" derating, which is strictly specific to these HPDs and based on the *trained-fit (i.e., near-optimal)* field NRR data (Table 3), would be at least 6 to 10 dB subtracted from the manufacturers' NRR values for the earplug and ear canal cap devices; and at least a 5 dB derating for the earmuff. This derating scheme assumes that appropriate HPD usage training is provided to the workers and that they fully adhere to these procedures. If this is not the case, and it often isn't in most industrial plants, the derating factor must increase to perhaps a 50% reduction of the manufacturer's NRR for the plugs and a 30-40% reduction for the muff.

Based on the prediction results, particularly those of the subject-fit data (Figures 13 through 16), estimating overall field noise protection (e.g., NRR_{PS}) by single 1/3-OB (e.g., centered at 500 Hz) data is accurate, practical, and feasible. Therefore, 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 workplace. Pure-tone industrial audiometers, which are readily available in the field, might alternatively be used for attenuation measurements in lieu of 1/3-OBs of noise. More work needs to be done to determine if the prediction results obtained under sound-field conditions are similar to those which might be obtained under standard audiometric headphones, which might prove useful for earplug attenuation monitoring in the field.

Finally, the results from both the laboratory and field studies suggest that laboratory simulation tests designed to mimic field influences on attenuation may only be expected to yield reasonable estimates of field performance for certain HPDs. Laboratory versus field attenuation agreement under identical fitting conditions was good for the earmuff, but not for either earplug tested. This indicates 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 of the field conditions, still demonstrated significant differences between the two settings (Figure 16). Although the earmuff's attenuation generally provided good agreement between the laboratory and field protocols, 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. Collectively, based on the attenuation contrast results, it is concluded that the field study results did not validate those of the laboratory study, especially for the insert-type HPDs; therefore, it appears difficult to devise a reliable, behavioral laboratory simulation protocol which accurately estimates true HPD field performance. However, more realistic laboratory test protocols, which closely reflect field conditions, still need to 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 a device-specific derating scheme to the resultant data is still quite likely, based on the findings of the field study reported herein.

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Park, M.-Y. and Casali, J. G. (1990b). A controlled investigation of in-field attenuation performance of selected insert, circumaural, and canal cap hearing protectors. Human Factors, accepted - in press.

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APPENDIX I

PUBLICATIONS RESULTING FROM GRANT



LIST OF PUBLICATIONS RESULTING FROM GRANT

- Casali, J. G. and Grenell, J. G. (1989). An exploratory study of moderate physical activity and selected design attribute effects on earmuff attenuation. American Industrial Hygiene Association Journal. 50(9), 480-485.
- Casali, J. G. and Park, M.-Y. (1990). Attenuation performance of four hearing protectors under dynamic movement and different user fitting conditions. Human Factors, 32(1), 9-25.
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- Casali, J. G. and Park, M.-Y. (1990). Highly kinematic work activity, temporomandibular movement, and user fitting effects on attenuation of selected HPDs. Invited presentation at the 1990 American Industrial Hygiene Conference, Special Session on Hearing Protection Devices, Orlando, Florida, May 13-18, 1990.
- Casali, J. G. and Park, M.-Y. (1991). Can laboratory experimental scenarios yield hearing protector attenuation data representative of actual workplace protection performance? Invited presentation to appear at the 1991 National Hearing Conservation Association Meeting, San Antonio, Texas, February 21-23, 1991.
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- Park, M.-Y. and Casali, J. G. (1990b). A controlled investigation of in-field attenuation performance of selected insert, circumaural, and canal cap hearing protectors. Human Factors, accepted - in press.

APPENDIX II

STATEMENT OF INVENTIONS

STATEMENT OF INVENTIONS

An earplug invention was developed during the period of the research project and a patent application was filed in July, 1990. This invention was developed concurrently with, but not as a direct outgrowth of the research project. In working on several hearing conservation-related projects, including the NIOSH grant, the Auditory Systems Laboratory research team was confronted with a number of fitting problems and practical disadvantages associated with the use of insert-type hearing protectors, especially those of the user-molded and custom-molded varieties. An effort was made to design a new earplug protector concept which would circumvent most of these problems, and provide an easily-fit, custom-molded personal hearing protector that would be replaceable in the field. Specific design details of the device are available under confidentiality agreement in the following technical report:

Casali, J. G., Mauney, D. W., and Berneman, L.P. Custom-molded multi-application foaming earpiece (CIT Case Number 135): A general concept overview for disclosure under confidentiality agreement. Blacksburg, VA: Virginia Tech, Dept. of Industrial and Systems Engineering, Technical Report 9005 (Audio Lab 10/23/90/3-HP), October, 1990. (Report available from the Virginia Center for Innovative Technology, CIT Tower, Herndon, VA.)

Inventors: J. G. Casali and D. W. Mauney, Virginia Tech. Patent application entitled "Custom-Fitting Earplug Formed In-Situ Using Foaming Action"

APPENDIX III

STATEMENT OF EQUIPMENT PURCHASED



STATEMENT OF EQUIPMENT PURCHASED

There were no equipment purchases made from this NIOSH grant with a unit acquisition cost of \$500.00 or greater.

