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Hearing protector attenuation: Models of attenuation distributions

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Current hearing protector rating standards estimate the protection performance for a given frequency as the mean attenuation minus a multiple of the standard deviation. Distributions of real-ear attenuation at threshold data are fit with maximum likelihood estimation procedures using both normal and mixed-normal models. Attenuations from six hearing protectors, Bilsom UF-1 earmuff, Bilsom Quietzone, E•A•R® Classic®, E•A•R® EXPRESS® Pod Plugs®, Howard Leight MAX, and Wilson EP100 earplugs, measured with a subject-fit protocol are reported. The mixed-normal (bimodal) model provides a better fit to the empirical data than the unimodal model for most frequencies and protectors. Primarily, the bimodal model fits the shape of the distributions caused by data from poorly-fit protectors. This paper presents an alternative method for estimating the protection performance either with the more accurate bimodal model or directly from the empirical cumulative distributions of the attenuation data. [DOI: 10.1121/1.1461835]

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I. INTRODUCTION

Real-ear attenuation at threshold (REAT) determines hearing protector attenuation as the difference between occluded and unoccluded thresholds for third-octave band noise stimuli at specified center frequencies from 63 to 8000 Hz depending upon the standard used. Three hearing protector fitting protocols have been defined in ANSI standards: experimenter-fit in ANSI S3.19-1974 (ANSI, 1974), experimenter-supervised-fit, and subject-fit in ANSI S12.6-1997 (ANSI, 1997).

ANSI S3.19-1974 provided for an experimenter fit when optimum protector performance was required. The subject was to fit the hearing protector, however the experimenter inspected the fit to assure a good fit and acoustic seal. The experimenter had the option of reinserting earplugs or readjusting other protectors to achieve a ''best'' fit. This method afforded the greatest control over the REAT testing. In fact, Franks *et al.* (1996) demonstrated that EF data exhibited the smallest lab-to-lab, subject-to-subject, and trial-to-trial variance while achieving the greatest mean attenuations. However, EF data have significantly overestimated real-world data as indicated by the derating of the noise reduction rating (NRR) by OSHA inspectors (Murphy and Franks, 1998, 2001; OSHA, 1983, 1999).

Similarly, the experimenter-supervised-fit (ESF) protocol described in Method A of ANSI S12.6-1997 also overestimates the real-world attenuation (Royster *et al.*, 1996; Berger *et al.*, 1998). The ESF protocol yields the greatest lab-to-lab variation, and has a tendency to include more data from subjects with poorly-fit protectors (Murphy and Franks, 1998). The European community uses a protocol similar to the ESF protocol described in ISO 4869-1 (1990) for estimating REAT for protectors. Calculation of the ISO Single Number Rating (SNR) and HML are accomplished with the REAT data collected under an ESF protocol. ANSI S3.19-1974, Method A of ANSI S12.6-1997, and the ISO ESF protocols prescribe the use of a fitting noise which aids the subject in achieving the best fit of the protector.

The subject-fit (SF) protocol (ANSI S12.6-1997, Method B) gives the subject control of fitting the device. Subjects tested under the SF protocol are required to be naïve with respect to hearing protector use and training. When tested, the subject is given a copy of the manufacturer's instructions and instructed that the experimenter is not allowed to assist in the fitting process. The SF data typically have the lowest mean attenuations of the three test protocols and the greatest subject-to-subject and trial-to-trial variances. The SF lab-to-lab variances were less than the ESF lab-to-lab variances and were comparable to the variances for the EF method (Murphy and Franks, 1998). The agreement between SF data and real-world data demonstrated that naïve subject performance was comparable to workers who were supposedly trained[1] in using earplugs (Berger *et al.*, 1998). The primary shortcoming with the subject-fit protocol is the increased prevalence of poorly-fit protectors. Murphy and Franks (1998) examined the distribution of attenuations from four protectors tested in interlaboratory studies using EF, ESF, and SF protocols and found that the premolded plugs, Bilsom Quietzone and Wilson EP100, exhibited bimodal dis-

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tributions for several test frequencies. The bimodal attenuation distributions often had a peak near 0 dB and another at about 20 dB which typified poorly-fit and well-fit protectors.

The NRR, SNR, high middle low (HML) and the noise reduction rating subject-fit (NRR_{SF}) are among several rating methods currently in use in the United States and Europe. The 1995 NIOSH Hearing Protector Compendium lists the rating method in use at that time. For details about the methods, one should consult the compendium and the appropriate standard (NIOSH, 1995; EPA, 1978; ISO, 1994; Berger and Royster, 1996; Franks *et al.*, 2000). In essence, the ratings are subtracted from the noise levels measured for a worker's station and yield an estimate of the noise levels under the protector (ANSI S12.19, 1996). Hearing protectors sold in the United States are required to be labeled under the EPA rule, 40 CFR 211, subpart B. The EPA rule requires that testing be done according to the EF protocol in the ANSI S3.19-1974 standard even though ANSI S12.6-1997 supercedes S3.19. European standards require that protectors be tested according to ISO 4869 part 1 and labeled according to ISO 4869 parts 2 and 3 which specify the SNR and HML rating methods.

One common element to each of these protected noise level calculations is the use of the mean attenuation minus some multiple of the standard deviation. Hence, the attenuation values are assumed to be normally distributed when describing the percentage of a protected population. In Murphy and Franks (1998), the low-frequency attenuation distributions for the Bilsom Quietzone and Wilson EP100 earplugs were non-normal and bimodal while the distributions for the E•A•R® Classic® and Bilsom UF-1 were unimodal and normal. This trend was most pronounced for the subject-fit data.

For this paper, the data measured in several laboratories for the four hearing protectors examined in Murphy and Franks (1998) and the data from two additional devices, the E•A•R® EXPRESS® Pod Plugs® and Howard Leight MAX earplugs, were analyzed. The assumption of normality was critically examined to determine its appropriateness as a descriptor of REAT data. The goal was to develop a more representative estimate of protection afforded by hearing protectors which can be used in current rating standards with minimal modification of the calculations of the rating values.

II. THEORY FOR BIMODAL DATA

The developments of the various rating methods have been predicated upon the assumption that data are well behaved. Attenuations for a hearing protector measured at several different frequencies are described by means and standard deviations. Consistent attenuation data are assumed to be normally distributed or at the least unimodal such that the protector has one way to fit the ear canal and that the continuum of attenuations measured at several frequencies are best characterized by a mean and standard deviation. Subject-fit test protocols provide more opportunity for the test subjects to improperly fit the protector to the ear. When the protector is improperly fit, the integrity of the protector's seal with the head can be compromised resulting in low attenuations due to leakage. Because SF protocols prohibit experimenter intervention to correct improper fits, the REAT measurements will exhibit more variability than ESF or EF protocols.

A. The Gaussian distribution

When sampling a population, the samples are assumed to be drawn randomly from a normally-distributed population,

$$g(x,\mu,\sigma)=\frac{1}{\sqrt{2\pi}\sigma}e^{-(x-\mu)^2/2\sigma^2}, \tag{1}$$

where x is a continuous variable, μ is the mean, and σ is the standard deviation. The Gaussian distribution is important to the hearing protector rating standards because multiples of the standard deviation are used to estimate the protection performance. Specifically, the protection performance for NRR, SNR, HML, and NRR_{SF} standards is

$$\text{Protection Performance}\,(\alpha)=\int_{\mu-\alpha\sigma}^{\infty} g(x)\,dx, \tag{2}$$

where $\alpha=2$ for the NRR, $\alpha=1$ for the NRR_{SF}, and α is variable but is normally set to 1 for the SNR and HML methods.

B. Bimodal attenuation distribution

A mixture of two Gaussian distributions can be used to create a bimodal distribution. Since no *a priori* knowledge of the bimodality is assumed, the data are apportioned between the two distributions. The combined distribution becomes

$$f(x)=\left(\frac{\phi}{\sqrt{2\pi}\sigma_1}e^{-(x-\mu_1)^2/2\sigma_1^2}+\frac{1-\phi}{\sqrt{2\pi}\sigma_2}e^{-(x-\mu_2)^2/2\sigma_2^2}\right), \tag{3}$$

where μ_1 and μ_2 are the means, σ_1 and σ_2 are the standard deviations, and ϕ is a proportionality constant with a range of 0 to 1.

Integration of $f(x)$ yields the bimodal cumulative distribution

$$F(x)=\phi\int_{\mu-\alpha\sigma}^{\infty} g(x,\mu_1,\sigma_1)dx + (1-\phi)\int_{\mu-\alpha\sigma}^{\infty} g(x,\mu_2,\sigma_2)\,dx, \tag{4}$$

where $g(x,\mu,\sigma)$ is the Gaussian function in Eq. (1). Figure 1 illustrates the mixed Gaussian distribution and its associated cumulative distribution function. The bimodal cumulative distribution has a characteristic shoulder between the two peaks. If the two distributions overlap considerably; the mixture of two normal distributions can look like a single, skewed distribution, or even resemble a single normal distribution.

III. METHODS

The data used in these analyses have been previously reported in several articles: Royster *et al.* (1996), Franks

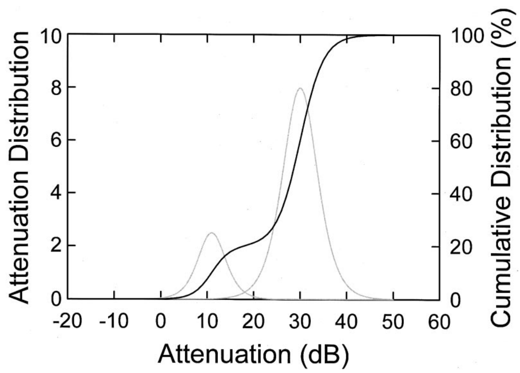

FIG. 1. The bimodal cumulative distribution derived from two normal Gaussian distributions. Different proportionality constants, means, and standard deviations affect the shoulder in this plot.

et al. (1996), Berger *et al.* (1998), and Franks *et al.* (2000). Data were collected at E•A•RCal laboratory, Wright Patterson Air Force Base, US Army Auditory Research Labs, Virginia Tech University, and at the NIOSH Taft Laboratories. Each of the studies collected and analyzed REAT data using the EF, ESF, or SF protocol(s). This paper analyzes the subject-fit data collected by these laboratories for the Bilsom UF-1 earmuff (UF-1), Bilsom Quietzone (Quietzone), E•A•R® Classic® (Classic), E•A•R® EXPRESS® Pod Plugs® (Express), Howard Leight MAX (MAX), and Wilson EP100 (EP100) earplugs.

The E•A•RCal, WPAFB, USAARL, and NIOSH laboratories tested the UF-1, Classic, V-51R, and EP100 hearing protectors with 24 subjects each and four REAT repetitions per subject in the four-lab interlaboratory study (Royster *et al.*, 1996) for a total of 96 subjects. In the two-lab study, Virginia Tech and NIOSH tested Classic and V-51R hearing protectors with 26 and 25 subjects, respectively, with three repetitions per subject in the two-lab study (Murphy and Franks, 1998) for a total of 51 subjects. The MAX earplug was tested with 24 subjects with three repetitions per subject and 24 subjects with two repetitions per subject. The Express earplug was tested with 20 subjects with two repetitions per subject (Franks *et al.*, 2000). Both the MAX and Express devices were tested at NIOSH. In order to make the data compliant with the ANSI S12.6 Method B protocol, the first two repetitions were used in the analysis. Within a frequency band, the REAT estimates were averaged over the first two trials to create a data set which did not have repeated measures for a subject. In Royster *et al.* (1996), the REAT data exhibited a lab-to-lab effect. While the effect is real, it was not subtracted from the laboratory averages because of the possibility that it resulted from different relative distributions of the well- and poorly-fit data.

Subjects were recruited from the communities surrounding the labs and were compensated for the participation. Subjects were prescreened to determine their lack of experience with hearing protector usage, training, and testing. They were trained to produce sound-field audiograms with a 6-dB range or better for each test frequency for three consecutive audiograms. Diffuse sound-field tests were conducted in reverberant chambers that satisfied the ANSI S12.6-1997 requirements. Specifically, the sound field should vary no more than ± 5 dB at a radius of 15 cm about the center of the subject's head and no more than 3 dB for the left–right axis. Pairs of unoccluded and occluded thresholds were measured for each subject. Between trials, subjects removed the hearing protection and, if using earplugs, were given a new pair of plugs to use on the next occluded trial.

IV. RESULTS

The REAT data were fit with both the single and mixed Gaussian models with the general optimization function **ms** in S-Plus (Venables and Ripley, 1997). The means (μ_1, μ_2), standard deviations (σ_1, σ_2), and proportionality constants (ϕ) are reported in Table I. The fits were then tested with a likelihood ratio test to determine whether the bimodal model fit was significantly better than the unimodal fit. A p value less than 0.05 was the criterion for statistical significance. Table II lists the p values for each of the comparisons of the fits.

The data in Table I exhibit some interesting trends. The proportionality constant tends to be low for those frequencies and protectors where the unimodal model gives a reasonable fit. The exception to this trend is the UF-1 earmuff. In cases where the two distributions overlap significantly, the mean for unimodal model is between the means of the bimodal fit, and the unimodal standard deviation is comparable to those fit for the bimodal model.

For the insert earplugs, $0.1 < \phi < 0.9$ tends to indicate bimodally-distributed data. For the Express at 125 Hz, the high proportionality constant, 0.913, resulted from the fitting optimization. The formulation of the theory is symmetric with respect to ϕ. A shoulder at about 0.1 can be seen in the 125-Hz Express panel in Fig. 2. This shoulder is also evident in the other panels for the Express. In all of these cases, the fitting algorithm captured the feature.

In Fig. 2, the cumulative probability distributions of the data, unimodal, and bimodal Gaussian models (y axis) are plotted against the cumulative probability of the unimodal Gaussian model (x axis). In this plot, the straight line is the normal probability plot that the data would overlay if it were normally distributed. The bimodal fit is plotted with a gray line. In several cases, notably the Quietzone and EP100, deviations about the straight line indicate non-normal behavior. Most of the deviations occur in the lower left portion of each panel which represent the minimum REAT for that given device and frequency.

The maximum-likelihood test of the unimodal and bimodal fit demonstrated that the bimodal model yielded a better fit in 27 of 42 cases. The bimodal model did not provide poor fits to the normally-distributed data, the fits were just not significantly better than the unimodal fits. Clearly, the Quietzone and EP100 data in Fig. 2 demonstrated greater propensity for bimodality at the low frequencies. At 2000 Hz and above, the low attenuation shoulders in the distributions were diminished. The bimodal fit to the Quietzone data was not significantly better at 4000 Hz than the unimodal fit. The Express cumulative distributions exhibited a variety of shapes. At 125 Hz, the distribution was normally distributed. At the other frequencies, the distributions appeared to have a shoulder at the low attenuations. The bimodal fits for 125

TABLE I. Fitting results for unimodal and bimodal models of attenuation.

Protector Model		Bilsom UF-1		E•A•R® Classic®		Wilson EP100		Howard Leight MAX		E•A•R® EXPRESS® Pod Plugs®		Bilsom Quietzone	
		Uni	Bi	Uni	Bi	Uni	Bi	Uni	Bi	Uni	Bi	Uni	Bi
125 Hz	μ_1	7.4	4.2	20.8	9.0	14.4	1.4	21.8	1.7	14.2	12.7	12.5	2.1
	σ_1	3.6	2.0	6.8	5.4	11.0	2.4	8.2	0.9	6.9	5.3	9.5	2.4
	μ_2		8.5		21.9		20.9		23.1		29.5		17.5
	σ_2		3.3		5.8		7.1		6.7		2.6		7.3
	ϕ		0.265		0.084		0.336		0.060		0.913		0.324
250 Hz	μ_1	14.2	11.3	21.6	10.0	14.3	1.9	22.4	1.8	15.2	3.6	11.9	1.7
	σ_1	29	3.6	6.3	4.3	10.7	2.5	8.8	1.1	6.6	2.5	9.1	2.3
	μ_2		14.7		22.1		20.9		23.7		18.0		16.6
	σ_2		2.3		5.9		6.7		7.4		3.4		7.0
	ϕ		0.163		0.039		0.349		0.059		0.198		0.313
500 Hz	μ_1	20.8	16.5	23.5	19.4	15.0	0.8	23.5	0.4	16.5	14.3	12.4	0.7
	σ_1	2.9	1.8	7.2	0.8	11.7	1.7	9.7	0.1	7.7	9.4	9.1	1.4
	μ_2		21.9		23.8		20.0		24.5		19.0		15.2
	σ_2		2.1		7.3		9.4		8.6		3.5		7.9
	ϕ		0.193		0.063		0.259		0.041		0.542		0.194
1000 Hz	μ_1	29.4	20.4	24.7	12.3	16.8	2.4	23.7	2.8	19.0	4.7	14.7	2.5
	σ_1	4.0	1.3	6.2	0.4	10.4	3.2	7.5	1.6	8.0	3.8	9.1	2.8
	μ_2		30.2		25.0		21.8		24.6		22.6		18.8
	σ_2		3.1		6.0		6.8		6.2		3.6		6.9
	ϕ		0.081		0.019		0.257		0.040		0.198		0.232
2000 Hz	μ_1	31.6	31.5	31.0	19.1	23.9	13.3	30.2	11.7	27.4	17.0	22.3	7.5
	σ_1	4.1	3.2	4.6	1.0	9.9	7.6	6.0	3.6	8.8	9.9	9.4	4.4
	μ_2		32.0		31.2		29.3		31.0		31.6		26.0
	σ_2		6.0		4.3		5.8		4.7		2.4		6.1
	ϕ		0.763		0.024		0.334		0.042		0.291		0.202
4000 Hz	μ_1	35.8	34.2	39.0	33.5	29.9	23.2	38.6	31.2	32.1	17.4	23.1	8.7
	σ_1	4.0	4.0	5.6	6.5	10.5	8.6	7.1	7.2	7.7	5.7	7.5	2.1
	μ_2		37.6		40.9		39.0		42.1		35.0		23.9
	σ_2		3.2		3.8		3.9		3.3		3.6		6.9
	ϕ		0.524		0.249		0.576		0.322		0.167		0.054
8000 Hz	μ_1	35.2	25.1	38.4	33.6	26.8	10.9	39.7	32.3	31.2	9.7	18.9	10.6
	σ_1	4.5	1.7	7.4	7.1	13.5	5.6	8.5	9.5	9.0	4.5	10.7	5.3
	μ_2		36.0		42.3		34.9		43.9		33.5		24.2
	σ_2		3.6		4.9		8.1		3.8		5.5		9.9
	ϕ		0.070		0.452		0.336		0.357		0.100		0.392

and 500 Hz were not significantly better than the unimodal fits. The fewer number of data points for the Express yield a rougher data plot and gave the appearance of a greater amount of noise in the data than for the EP100 and Quietzone devices.

The Classic data were more normally distributed. At 4000 Hz, the Classic data had a slight shoulder at the lower attenuations. Only for the 4000 and 8000 Hz distributions were the bimodal fits significantly better than the unimodal fits. The cumulative distributions for the MAX earplug were more noisy than the Classic due to fewer data points. The MAX cumulative distributions had a small shoulder at 1000 Hz and below. At 4000 and 8000 Hz, the distributions deviated from the unimodal fit in the middle sections. The bimo-

TABLE II. The results of maximum likelihood ratio tests. The p values which are less than 0.05 are in bold type and indicate that the bimodal model provides a better fit than the unimodal model.

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Bilsom Quietzone	**6.46×10^{-9}**	**1.60×10^{-8}**	**2.21×10^{-7}**	**6.69×10^{-5}**	**2.10×10^{-5}**	3.11×10^{-1}	**6.25×10^{-3}**
Bilsom UF-1	4.43×10^{-1}	1.31×10^{-1}	7.47×10^{-2}	**3.22×10^{-3}**	3.89×10^{-1}	8.03×10^{-1}	**2.15×10^{-2}**
E•A•R® Classic®	2.34×10^{-1}	8.89×10^{-1}	3.33×10^{-1}	4.74×10^{-1}	1.75×10^{-1}	**1.92×10^{-4}**	**4.90×10^{-2}**
E•A•R® EXPRESS®	4.07×10^{-1}	**2.50×10^{-2}**	5.32×10^{-1}	**5.83×10^{-3}**	**4.12×10^{-4}**	**1.02×10^{-2}**	**5.42×10^{-2}**
Howard Leight MAX	**1.21×10^{-2}**	5.15×10^{-2}	**7.18×10^{-3}**	7.61×10^{-2}	**1.84×10^{-2}**	**1.65×10^{-3}**	**9.67×10^{-4}**
Wilson EP100	**1.72×10^{-9}**	**3.54×10^{-9}**	**5.88×10^{-8}**	**3.10×10^{-5}**	**1.40×10^{-2}**	**2.47×10^{-4}**	**1.39×10^{-4}**

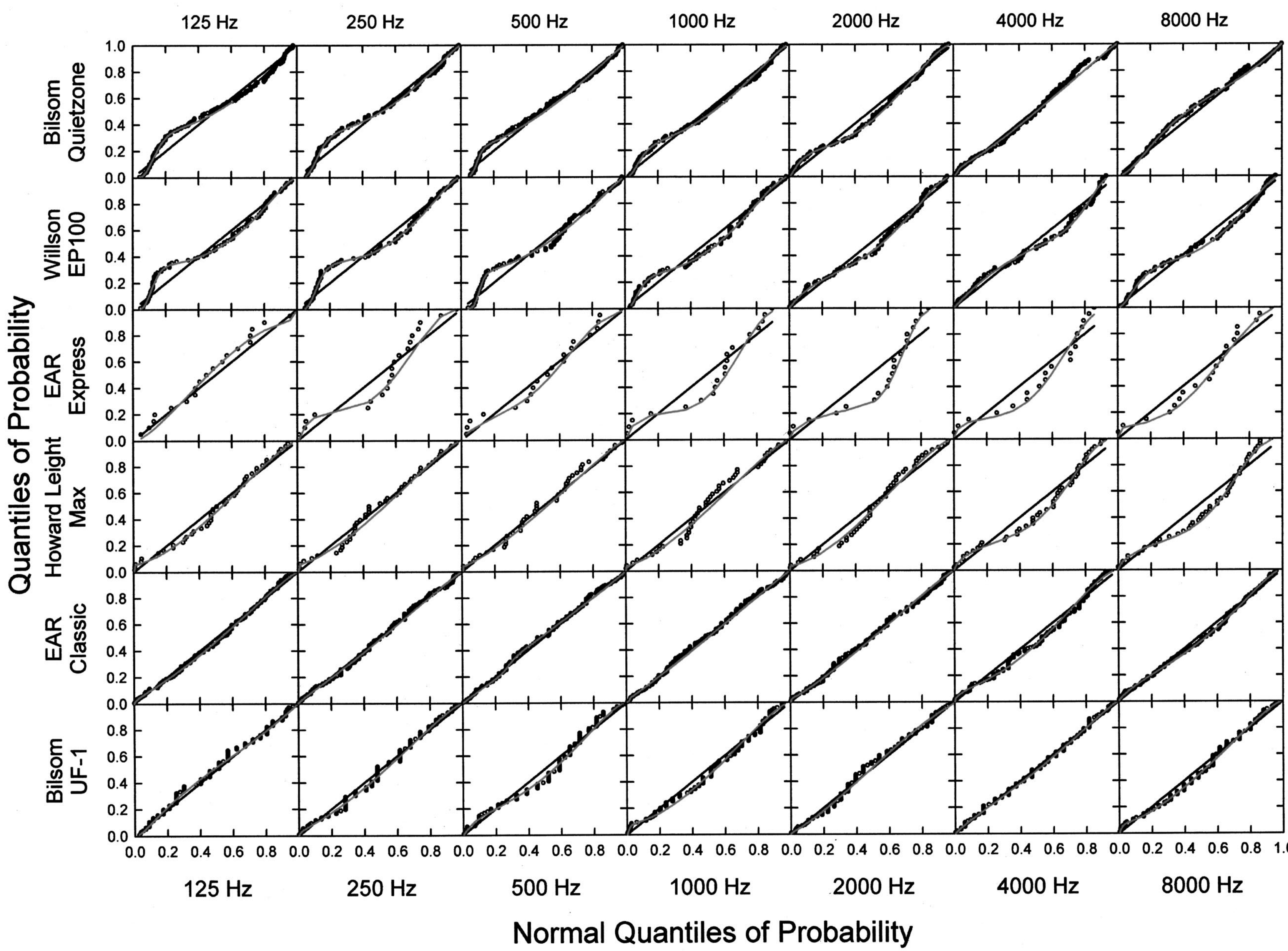

FIG. 2. Normal probability plots for six hearing protectors measured at 125, 250, 500, 1000, 2000, 4000, and 8000 Hz. The abscissa coordinates are the unimodal Gaussian quantiles. The ordinate coordinates are the probability of the cumulative distribution. The empirical data are shown as circles. By definition, the unimodal Gaussian fits are the straight black lines. The bimodal fits are the gray lines.

TABLE III. Comparison of the 16th percentile derived from the empirical data, and the bimodal and unimodal models. The values in the table are in dB and represent attenuations associated with each protector at the beginning of the rows.

	Model	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Bilsom	Empirical	1.6	1.5	1.5	3.5	10.9	15.7	8.6
Quietzone	Bimodal	1.9	1.6	1.3	3.5	10.7	15.5	8.2
	Unimodal	3.1	2.9	3.3	5.6	12.9	15.6	8.2
Bilsom	Empirical	4.0	12.0	17.6	25.6	28.5	32.0	31.1
UF-1	Bimodal	3.7	11.6	17.7	25.9	27.9	31.8	31.3
	Unimodal	3.8	11.3	17.9	25.4	27.6	31.8	30.8
E•A•R®	Empirical	14.3	15.7	17.0	19.0	27.0	34.3	31.3
Classic®	Bimodal	14.4	15.4	16.8	18.6	26.6	34.0	30.7
	Unimodal	14.1	15.3	16.4	18.6	26.4	33.5	31.0
E•A•R®	Empirical	6.4	7.0	8.0	11.0	22.3	27.1	26.8
EXPRESS® Pod Plugs®	Bimodal	7.8	5.8	9.2	8.0	18.2	25.8	25.3
	Unimodal	7.3	8.6	8.8	11.1	18.7	24.4	22.2
Howard Leight	Empirical	15.2	16.9	16.2	17.8	25.8	31.3	32.3
MAX	Bimodal	14.8	14.6	14.6	17.4	25.6	31.2	31.1
	Unimodal	13.6	13.7	13.9	16.3	24.2	31.6	31.3
Wilson	Empirical	1.5	1.6	1.1	2.9	11.6	18.0	10.3
EP100	Bimodal	1.2	1.6	1.0	3.3	12.8	18.1	10.5
	Unimodal	3.5	3.7	3.4	6.4	14.1	19.4	13.4

dal fits were significantly better at 125, 500, 2000, 4000, and 8000 Hz.

The UF-1 data exhibited smooth responses at all frequencies which were close to the normally-distributed ideal. The bimodal model was judged more likely than the unimodal only at 8000 Hz.

For each frequency, a linear interpolation of the data points bracketing the 16th percentile (0.1573) was used to estimate equivalent $\mu - 1\sigma$ of the empirical cumulative distribution. The 16th percentile of the unimodal model was calculated directly as $\mu - 1\sigma$. For the bimodal model, the cumulative distribution was numerically solved for the attenuation at the 16th percentile. The results for the six devices are compared in Table III. For the Quietzone, large discrepancies between the unimodal and the empirical estimates of the 16th percentile were evident below 4000 Hz. The bimodal model was within 0.3 dB of the empirical estimate at all frequencies. The bimodal estimate was closer than the unimodal at all frequencies except 4000 Hz where the unimodal was 0.1 dB less than the empirical.

Similarly for the EP100, the bimodal estimates were closer to the empirical data than the unimodal at all frequencies. The unimodal estimates overestimated the 16th percentile by as much as 3.5 dB at 1000 Hz. At 2000 Hz, the bimodal differed by 1.2 dB while the unimodal differed by 2.4 dB.

The best estimates for the Express were mixed between the bimodal and the unimodal models. At 250, 4000, and 8000 Hz, the bimodal model gave a better estimate of the empirical data. At 1000 Hz, the difference between the bimodal model and the data was 3.0 dB. The unimodal model gave a better estimate of the data at 125 and 2000 Hz even though the data were apparently distributed bimodally. If additional data were collected for the Express, the cumulative distributions would be expected to exhibit less noise and would potentially be better fit by both the bimodal and unimodal models.

The bimodal model 16th percentile estimates for the Classic fits exhibited good agreement with the data. At 125 Hz, the bimodal estimate differed by 0.1 dB and was within 0.4 dB at 500 and 1000 Hz. At other frequencies, the bimodal model was within 0.1 dB. The unimodal model differed by 0.8 dB at 2000 Hz and 0.7 dB at 4000 Hz. At other frequencies, the unimodal fits were within 0.5 dB of the empirical data.

The unimodal fits to the MAX data exhibited more discrepancy than the corresponding fits to the Classic data. At 125 Hz, the unimodal fit was off by 0.7 dB while the bimodal fits were off by 1.6 dB at all other frequencies. The bimodal model provided a better estimate of the 16th percentile.

Lastly, the bimodal model provided a better fit than the unimodal model at most of the frequencies for the UF-1 data. At 4000 Hz, the two estimates were the same. At 125 and 1000 Hz, the unimodal estimate was 0.1 dB better than the bimodal estimate. The bimodal estimate was never more than 0.6 dB different from the empirical estimate while the unimodal estimate was 0.9 dB less than the empirical estimate at 2000 Hz.

V. DISCUSSION

The unimodal and bimodal models presented in this paper have been examined for how well they describe subject-fit REAT data. The unimodal model is limited in its ability to describe the results, and yet the unimodal Gaussian distribution forms the basis of data analysis for the current rating standards and rules. In particular, the SNR rating method (ISO 4869−2) calculates the assumed protected value as

$\mu - \alpha\sigma$, where α is variable. The NRR uses $\alpha = 2$ and the NRR_{SF} uses $\alpha = 1$. While the standards never explicitly state the assumption of normality, it is implicit in the treatment of the data. Therefore, the validity of the assumption should be tested before applying the Gaussian method. Murphy and Franks (1998) explicitly tested normality and demonstrated the V51R and EP100 data were not normally distributed.

The use of subject-fit protocols almost certainly guarantees that future hearing protector REAT data will include results from poorly-fit protectors. Consequently, standards which assume well-behaved data require revision to include testing of the assumption of normality and need to accurately model the data. The analysis of these data demonstrates the bimodal model yields better fits in most cases and does a better job of predicting the assumed protected values at the 16th percentile.

One difference between ANSI and ISO subject-fit protocols should be noted. The ANSI S12.6-1997 Method B specifically requires that the test subjects be naive with respect to hearing protector use and training. The ISO standard has no such requirement and, consequently, the experience with hearing protector use is uncontrolled. In particular, the poor performance of some earplugs can be remedied by training subjects in proper insertion technique and how to use fitting noise to identify a poorly sealed protector. However, the ISO 4869-1 values tend to overpredict the real world attenuation of hearing protectors whereas the Method B data fall within the upper quartile of real world measurements (Berger *et al.*, 1998).

The analysis presented here is not specifically dependent upon the use of a Gaussian distribution. Earlier formulations (Murphy and Franks, 1999a, 1999b) utilized the logistic distribution to model the bimodal distributions. The analytic solution for the cumulative distribution yielded a simpler analysis. Other statistical distributions may prove to be more appropriate for fitting skewed data distributions. The unimodal Gaussian distribution has been critically examined and found inadequate when the attenuation data are contaminated with poorly-fit protectors.

VI. CONCLUSIONS

This paper has sought to develop a better approach to model the attenuation of hearing protectors. With the advent of new standards which utilize the subject-fit protocol, testers have relinquished control over how test subjects will fit the hearing protector. Similarly, the manufacturer has no control over how the workers wear their hearing protectors. Because of this fundamental change in the control of data integrity, the assumption of normality is not guaranteed. Therefore, the bimodal model addresses the problem of non-normal distributions of REAT data and more accurately models the variety of data. The standards-setting bodies, ANSI and ISO, have the responsibility to develop scientifically defensible standards. Future ANSI and ISO standards for rating the noise reduction of hearing protectors should be based on accurate models of the attenuation distribution. Determination of the protection performance directly from the cumulative distribution or from the bimodal fit to the data would remedy this shortcoming in the current HPD rating standards. At the very least, ISO and ANSI standards could be based on empirical quantiles which do not assume any particular attenuation distribution.

[1]OSHA's construction standard, 29 CFR 1926.101(b), titled: "Hearing Protection," requires "ear protective devices inserted in the ear shall be fitted or determined individually by competent persons." Workers are typically given little training in the proper use of insert earplugs as can be seen by visual inspection of workers's earplugs at numerous occupational settings.

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