Comparison of the noise attenuation of three audiometric earphones, with additional data on masking near threshold[a]

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The noise-excluding properties of a standard supra-aural audiometric earphone, a widely used circumaural-supra-aural combination, and an insert earphone sealed to the ear with a vinyl foam eartip were measured in a diffuse-field room complying with ANSI S12.6-1984. Data on attenuation were obtained monaurally with the nontest ear plugged and muffed. Results for the supra-aural earphones generally agreed well with previously reported measurements. A broadband masking noise was used to directly test the ANSI S3.1-1977 permissible background noise levels for measuring to audiometric zero using standard audiometric earphones. This "ANSI noise" raised the average thresholds of 15 normal-hearing test subjects by 3 to 5 dB at the octave frequencies from 500 to 4000 Hz. With a noise conforming to the less stringent OSHA-1983 regulation, average thresholds were elevated 9 to 17 dB. An "ENT office noise" with an overall sound level of 54 dBA raised average thresholds even further, by as much as 29 dB at 500 Hz. Use of the circumaural system in the office noise limited the threshold elevation to 11, 5, 2, and 0 dB at the four octave frequencies tested. With the fully ("deeply") inserted foam eartips, the threshold elevation in the simulated office noise was 2 dB or less at all test frequencies. Actual threshold elevations agreed closely with predictions based on a critical ratio calculation utilizing measured sound field noise levels and measured earphone attenuation values.

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INTRODUCTION

One of the difficulties with standard audiometric earphones is their relatively poor noise-excluding properties, especially at low frequencies where background noise is usually greatest. At 250 and 500 Hz, for example, the 40- to 45-dBA background noise in a typical room produces a masked open-ear threshold, which is equivalent to a 20- to 25-dB hearing loss (Killion and Studebaker, 1978), and the commonly used MX-41/AR ear cushion provides little if any attenuation at those frequencies. A "soundproof" booth is thus required for accurate hearing testing in most situations.

Unfortunately, testing must often be done in situations where a soundproof booth is impractical: Bedside testing in hospitals for ototoxic drug monitoring, on-site testing of invalids in homes or nursing homes, and screening audiometry in schools are examples. The necessary testing done in those cases results in compromised audiometric data.

A problem also exists among smaller industries that must administer annual audiograms to their noise-exposed employees as required by the OSHA hearing conservation amendment (1983). Although the permissible ambient noise levels specified in that regulation are rather lax (as discussed later in this paper), in nearly all cases, an audiometric test booth is required. Often the cost of and space required by such a setup are prohibitive, or the ambient noise levels may be so great that additional attenuation beyond that provided by the test booth is required. In short, there are many instances when hearing sensitivity must be measured in which the cost, performance, and/or inconvenience of a bulky "portable" soundproof booth create the desire for alternative options.

One alternative is the use of an insert earphone that employs a shoulder-mounted transducer assembly that is coupled to the ear through approximately 25 cm of tubing. A preferred method of sealing such a device to the ear is through a disposable foam eartip of the type that can provide, when worn as a hearing protector (earplug) without the central hole and sound tube, some 30 to 45 dB of noise attenuation (Berger, 1986). Such values of attenuation are greater than or equal to that provided by conventional single-wall soundproof booths in the frequency range from 125–500 Hz.

Clemis *et al.* (1986) reported 15 to 25 dB less threshold shift for an insert earphone than for conventional supra-aural audiometric earphones when eight subjects were first tested in quiet and then in a 96-dBA high-level noise field, and demonstrated that the measured attenuation for the insert earphones permitted accurate testing to 0 dB HL, without the need for a sound booth, in the measured noise spectra of two actual ENT office settings. Testing to 0 dB HL was also possible except at 500 Hz in a downtown Chicago ENT office setting, and accurate testing down to approximately 15 dB HL between 125 and 1000 Hz and to 0 dB HL above

those frequencies was possible with the insert earphones even in the high noise levels of a hospital intensive care unit.

Our first objective in the present experiments was to obtain further data on the relative noise exclusion of insert earphones (ER-3A) and supra-aural TDH-type earphones, and also of a commercially available, noise-excluding circumaural earphone enclosure, the Audiocup. "TDH-type earphones" refers to the closely related TDH-39, TDH-49, TDH-50, and TDH-50P drivers mounted in either MX-41/AR or Telephonics P/N 51 supra-aural cushions. See Fig. 1 and Table I for additional information.

Our second objective was to gather direct experimental data on the adequacy of both the existing ANSI Standard (ANSI S3.1-1977) and OSHA (1983) requirements for allowable background noise during audiometric testing.

Our third objective was to verify the computational procedures on which the recommendations in ANSI S3.1-1977 were based, among them the use of only a 3-dB correction to the calculated allowable noise levels in order to prevent more than a 1-dB threshold elevation above true quiet. Although a 6-dB correction would be required on a power-law-summation basis, the standard states that "The 3-dB correction leaves a 1-dB threshold elevation."

Finally, we set out to establish further experimental data on the suitability of the insert earphones for testing in typical ambient noise levels outside a sound booth.

I. PROCEDURE

A. Audiometric method

Monaural fixed-frequency Békésy threshold tracings were obtained for the right ear of 15 subjects—8 females and 7 males—under various test conditions. Dwell time at each frequency was 30 s with an attenuator slew rate of 5 dB/s. The visually judged average midpoint of typically eight or more reversals was recorded as the threshold value at each frequency. An *ad hoc* analysis of similar data from prior experiments yielded a standard deviation (s.d.) of approximately 1.5 dB for individual thresholds obtained in this manner.
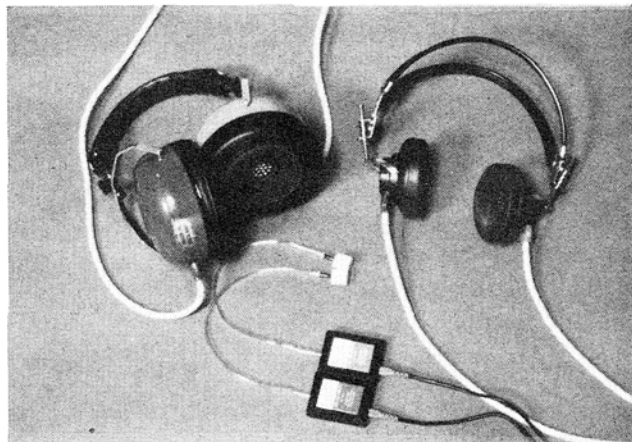

FIG. 1. Photograph of the three audiometric earphones evaluated in this study. Clockwise from upper left: Audiocups, TDH-50P + MX-41/AR, and ER-3A tubephones.

B. Earphone fitting

The fitting of the earphones was done by the experimenter in each case and not by the subject. For the TDH-50P + MX-41/AR and the Audiocups, the fitting was visually determined by aligning the center of the earphone diaphragm with the ear canal entrance. The ER-3A was configured with ER3-14 eartips that consist of plastic tubing inserted through 12-mm-long E-A-R® foam earplugs. The ER3-14 eartips were fully ("deeply") inserted so that the outside surface was inside the ear canal 2 to 3 mm past the floor of the concha, as recommended by the manufacturer.

C. Attenuation measurements

The attenuation provided by a given earphone was derived from the difference between the sound field thresholds obtained with the test ear uncovered and then covered by the earphone under test, in accordance with the real-ear-attenuation-at-threshold (REAT) method of ANSI S12.6-1984. The test signals were one-third octave bands of noise centered at each of the octave frequencies from 125 Hz through 8 kHz. These were presented in the 113-m³ reverberant room described by Berger and Wright (1979), a diffuse-field facility complying with the aforementioned standard.

D. Masking noises

The effect of ambient noise level on earphone thresholds was determined from the difference between the earphone *thresholds obtained in quiet and in a masking noise* presented via loudspeakers. The test signals were pure tones delivered through the right earphone at 500, 1000, 2000, and 4000 Hz. The masking noise was one of three broadband noises that we designated "ANSI noise," "OSHA noise," and "ENT noise." The one-third octave-band spectra of the three masking noises, measured at the center-head location (subject absent), are shown in Fig. 2.

The noises were created using a GenRad 1925 multifilter to shape a pink noise source, the output of which was then recorded onto a Revox A77 MK IV tape recorder for playback during testing. The noises are described as follows.

(1) ANSI noise: corresponded to the maximum permissible one-third-octave background noise levels for testing under TDH-type earphones mounted in MX-4l/AR cushions as given in ANSI S3.1-1977, except that the level at 8 kHz, which was judged objectionably loud and unlikely to occur in a real test environment, was arbitrarily reduced by 6 dB. The overall A-weighted level was 45 dB SPL.

(2) OSHA noise: corresponded to the allowable octave-band noise levels for testing under TDH-type earphones mounted in MX-4l/AR cushions, as given in the OSHA hearing conservation amendment (1983), except that the *levels at 4 and 8 kHz were arbitrarily reduced by 5 and 10 dB,* respectively, following the reasoning for the 8-kHz reduction in the ANSI noise described above. No specifications for the 125- and 250-Hz octave-band levels are found in the OSHA regulation, so we chose levels that provided a spectrum shape consistent with typical real-world, low-frequency masking noises. The overall A-weighted level was 55 dB SPL.

TABLE I. Description of earphones and earmuffs evaluated in this study.

Device	Description	Headband force (N)	Notes
TDH-50P + MX-41/AR	Telephonics 50-Ω earphone mounted in standard MX-41/AR cushion	5.3	referenced in ANSI S3.6-1969 (R 1986)
Audiocup	Amplivox circumaural noise-excluding cup enclosing a resiliently mounted TDH-50P + MX-41/AR	17.8	cup volume = 320 cm^3
ER-3A	Etymotic Research insert audiometric earphone consisting of a 50-Ω transducer coupled to the ear canal via a plastic tube passing through a shortened E-A-R foam earplug (ER3-14 eartip).	not applicable	tube length = 250 mm tube i.d. = 1.37 mm plug height = 12 mm
Model 3000	E-A-R Division circumaural noise-excluding earmuff with plastic headband and foam-filled cushions	12.5	cup volume = 220 cm^3

(3) ENT noise: set to match the octave-band spectrum measured by Clemis et al. (1986) in an "ENT examining room" without a soundproof booth (see Fig. 4 of their paper), but increased in level by 7 dB in order to create a noise that we estimated would just begin to mask thresholds measured with properly fitted insert earphones. This gave a spectrum with a slope of about − 6 dB/oct and a shape closely approximating the "C − A = 10 dB" curve of Botsford (1969). The overall A-weighted level was 54 dB SPL.

The masking noises were presented via the same three loudspeaker arrays that were utilized for the REAT measurements. The arrays were situated orthogonally to one another within the reverberant room in order to create a diffuse sound field (Berger and Wright, 1979). Three separate measurements of the overall spectra were made for each noise: at the beginning, during, and at the end of the experiment. At each of the standard octave frequencies, the nominal measured levels fell within 1.5 dB of the predetermined levels described above. The actual presentation levels of the masking noises for each subject were individually set to account

for differences in their hearing sensitivity (see Sec. I F below).

The condition later referred to as "quiet" represents the background noise of the chamber, approximately 10 dBA. At all test frequencies, these levels were inaudible to all subjects and created no masking for unoccluded listening (Berger, 1981).

E. Occluding the nontest ear

During all REAT and masked-threshold experiments, the left (nontest) ear of each subject was occluded with a deeply inserted E-A-R Plug. For the tests of the TDH-type earphones and the Audiocups, those devices also occluded the nontest ear, so that the ear was doubly protected.

Previous measurements indicated that the only case in which our procedure would still allow some participation of the nontest ear was in the REAT evaluations of the ER-3A, since the attenuation of that device approached to within a few dB of the attenuation of a deeply inserted E-A-R Plug at certain frequencies. This could have caused an underestimation of ER-3A attenuation of up to 3 dB if the ER-3A eartip provided as much attenuation as the plug in the nontest ear.

No participation of the occluded nontest ear in the room-noise-masked-thresholds portion of the experiment was expected, because the signal was presented only to the test ear and the threshold of the test ear was elevated less than about 30 dB, even with the worst noise and the poorest noise-attenuating earphone. This is 10–15 dB less than the minimum interaural attenuation of any of the earphones, so the effective signal delivered by cross-head hearing was presumably 10–15 dB below the threshold of the nontest ear at all times during those experiments.

F. Detailed description of the test session

Each of the 15 subjects sat through three test sessions lasting approximately 50 min each, one test session for each earphone. Fourteen sets of thresholds were obtained in each session.

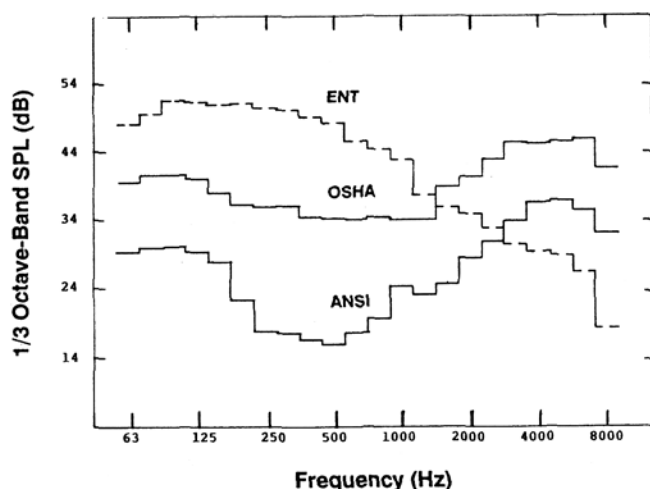(1) and (2) Two pure-tone audiograms were obtained

FIG. 2. One-third octave-band SPLs of the three masking noises set at overall sound levels of 54 dBA for the ENT noise, 55 dBA for the OSHA noise, and 45 dBA for the ANSI noise.

at 0.5, 1, and 2 kHz using a TDH-50P + MX-41/AR earphone with a headband force of 5.3 N. The earphone was removed and refit between the first and second audiogram. The data were averaged across replications and frequency to provide a single "baseline threshold." The baseline threshold value from the first of the three sessions was subsequently used to individually set the overall presentation level of the masking noises for each subject in order to normalize all noise-masking measurements, as if each subject had exactly 0-dB HL average baseline thresholds. Across subjects, the average adjustment in the presentation level of the masking noises was − 1.3 dB, with the largest adjustment having a value of − 6.0 dB.

(3) Sound field thresholds were obtained for the open test ear using one-third octave bands of noise centered at each of the octave frequencies from 125 Hz through 8 kHz.

(4) Sound field thresholds were obtained as above (3) with the earphone under test occluding the test ear.

(5) through (8) With the test earphone still in position, pure-tone earphone thresholds at 0.5, 1, 2, and 4 kHz were then obtained in quiet and in each of the three masking noises. The order of testing for the four conditions (quiet, ANSI noise, OSHA noise, ENT noise) was randomized across subjects and sessions, but was fixed across replications within a given session.

(9) through (14) Replication of (3) through (8).

The test session for the ER-3A earphone was extended to include four additional sets of thresholds in order to obtain REAT data (test and retest) on the combination of the ER-3A with an E-A-R Model 3000 circumaural earmuff (see Table I). For these tests, the ER-3A eartips were first inserted normally and then the earmuff was placed over the subject's ears in the headband-over-the-head arrangement as it is commonly worn for hearing protection. The ER-3A sound tubes formed a small loop at the ear and passed under the earmuff cushion below the ear.

G. Computation of the masked thresholds

The expected shifts in the pure-tone thresholds due to the masking noises were calculated for each earphone by utilizing data from classical masking experiments. These data, expressed as the difference in decibels between the threshold level of a pure tone and the pressure spectrum level (PSL) of the broadband noise that just masked it, were at one time referred to as critical bands (Hawkins and Stevens, 1950), but have come to be called critical ratios (Scharf, 1970). (When critical-ratio data are utilized in this manner, without converting them to an equivalent bandwidth, it is unnecessary to make any assumptions regarding the width of the band of noise frequencies responsible for masking.) The equivalent masking noise was computed by presuming that the external masking noise added to the apparent internal (threshold-determining) noise level of the ear on a power-law basis in accordance with the findings of French and Steinberg (1947). [The same computational procedure had been verified on two previous occasions by comparison to empirical data (Berger, 1986; Berger and Kerivan, 1983) and is further validated by the analysis presented in Fig. 14.]

The details of the computation may be found in Table II, which illustrates the procedure for one earphone/masking noise condition. The steps in the table can be simplified by use of the following equation:

$$MT = 10 \log(10^{[N - (TB - CR) - MAFD]/10} + 1). \quad (1)$$

The terms in the equation may be defined by reference to the following line numbers in Table II:

MT (masked threshold *re*: 0 dB HL); line (12),
N   (1/3 OB level of masking noise
    at ear);   line (6) − (7),
TB (1/3 OB to PSL correction);   line (8),
CR (critical ratio);   line (4),
MAFD (minimum audible field, diffuse); line (3).

The term inside the square brackets in Eq. (1) is the effective level (Z), as used by Hawkins and Stevens (1950).

II. RESULTS

A. REAT measurements

The mean and standard deviation of the attenuation values measured for each earphone are given in Table III and shown in Fig. 3. The TDH-50P + MX-41/AR used with 5.3-N headband force provides little attenuation below 1 kHz. The Audiocups, used with 17.8-N headband force, provide approximately 10-dB attenuation at 125 and 250 Hz with 24- to 39-dB attenuation at 500 Hz and above. The ER-3A provides 32- to 42-dB attenuation at all audiometric frequencies, and the ER-3A plus E-A-R 3000 earmuff, used with 12.5-N headband force, provides more than 45-dB attenuation above 125 Hz except at 2000 Hz.

Figures 4 and 5 show a comparison between our REAT measurements and previously reported measurements for the TDH-type earphone in the MX-4l/AR cushion and in the Audiocup, respectively. There is generally good agreement among the results in Fig. 4 for the frequencies up through 1 kHz with the spread in data increasing above 1 kHz. The data of this study lie among the lower attenuation values between 2 and 6.3 kHz, especially with respect to the values cited in ANSI S3.1-1977. In Fig. 5, the agreement between the current study and Murray and Waugh (1988) is exceptionally close; even the manufacturer's data agree well except at 2 kHz. The 3.15- and 6.3-kHz disparities between the manufacturer's data and the other two reports in Fig. 5 may be illusory, since no measured data from this study or from Murray and Waugh were provided at those specific frequencies.

Figure 6 provides a comparison between our REAT measurements on the ER-3A and a recently published study by Clark and Roeser (1988). The probable explanation for the lower attenuation measured by Clark and Roeser is that neither their "shallow" nor their "deeper" insertions, as described in their paper, actually conformed to the manufacturer's recommended insertion depth or to the protocol used in this study. Further evidence supporting this explanation is provided by a similar family of curves reported by Berger (1983), which demonstrates the strong influence of insertion depth of E-A-R Plugs on measured attenuation. For additional consideration of the importance of insertion depth, see Sec. III.

TABLE II. Derivation of the calculated threshold shifts in noise, using data for the TDH-50P + MX-41/AR earphones worn in the OSHA noise. Calculations based upon power-law summation of the masking noise and the apparent internal physiological noise.

		Frequency (Hz)						
		125	250	500	1000	2000	4000	8000
(1)	Monaural minimum audible pressure at eardrum — MAP (dB SPL)[a]	30	19	12	9	15	13	14
(2)	Eardrum response in a diffuse field— P_D/P_{DF} (dB)[b]	0	1	2	4	10	11	8
(3)	Monaural minimum audible pressure in a diffuse field — MAFD (dB SPL)[c]	30	18	10	5	5	2	6
(4)	Critical ratio — CR (dB)[d]	18.2	17.1	17.1	18.0	19.9	23.1	27.7
(5)	Pressure spectrum level (PSL) of apparent internal noise re: diffuse field (dB SPL)[e]	11.8	0.9	− 7.1	− 13.0	− 14.9	− 21.1	− 21.7
(6)	1/3 OB sound field level of masking noise (dB SPL)[f]	40	36	34.5	34	40.5	45.5	42
(7)	Earphone attenuation (dB)[g]	6.5	5.4	6.0	11.7	17.0	22.2	22.7
(8)	1/3 OB to PSL correction — TB (dB)[h]	14.6	17.6	20.6	23.6	26.6	29.6	32.6
(9)	Computed PSL of masking noise (dB SPL)[i]	18.9	13.0	7.9	− 1.3	− 3.1	− 6.3	− 13.3
(10)	PSL of total effective masking noise (dB SPL)[j]	19.7	13.3	8.0	− 1.0	− 2.8	− 6.2	− 12.7
(11)	Masked hearing threshold level (dB SPL)[k]	37.9	30.4	25.1	17.0	17.1	16.9	15.0
(12)	Calculated threshold shift due to masking, re: 0-dB HTL — MT (dB)[l]	7.9	12.4	15.1	12.0	12.1	14.9	9.0

[a] As reported in abstract and Fig. 5 of Killion (1978).

[b] Ratio of the eardrum pressure response (P_D) to diffuse-field sound-pressure levels (P_{DF}), as averaged from Killion and Monser (1980), Kuhn (1979), and Shaw (1980).

[c] Row (3) = row (1) − row (2).

[d] Threshold level of a pure tone minus the pressure spectrum level (PSL) of broadband masking noise, as summarized in Table I of Killion (1976).

[e] Apparent PSL of the internal physiological noise. Row (5) = row (3) − row (4).

[f] Measured levels of OSHA noise, this study.

[g] Measured mean 1/3 octave-band attenuation of the TDH-50P + MX-41/AR, this study.

[h] Computed as $10\log(BW)$ where BW is the measurement bandwidth for a 1/3 octave band that is defined as $0.232(f_c)$, where f_c is the filter center frequency.

[i] Row (9) = row (6) − row (7) − row (8).

[j] Computed as the energy addition of (5) and (9). For example, at 1000 Hz, the effective masking noise is $10\log(10^{(-13.0/10)} + 10^{(-1.3/10)})$.

[k] Row (11) = row (10) + row (4).

[l] Row (12) = row (11) − row (3).

Figure 7 shows a comparison of our REAT measurements on the ER-3A to previous REAT measurements for the standard E-A-R Plug by itself and for the E-A-R Plug used with a centrally located tube as a temporary earmold with a behind-the-ear hearing aid (Berger, 1987). The presence of the sound tube appears to reduce the E-A-R Plug attenuation by roughly 5 dB at all frequencies. We suspect this is due to sound leakage through the walls of the tube.

Figure 8 shows a comparison between the estimated

limits of attenuation due to bone conduction (entire-skull pickup of the sound in the diffuse field) and the measured attenuation of the ER-3A plus E-A-R 3000 earmuff. The latter combination appears to provide attenuation, at 250 Hz and above, within 2 to 5 dB of the estimated bone-conduction limits.

TABLE III. Real-ear attenuation at threshold for three earphones and an earphone-plus-earmuff combination. Values in dB.

| Frequency (Hz)	125	250	500	1000	2000	4000	8000
TDH-50P + MX-41/AR							
mean attenuation	6.5	5.4	6.0	11.7	17.0	22.2	22.7
s.d.	4.8	5.0	5.3	4.8	5.6	5.4	6.3
Audiocups							
mean attenuation	11.2	9.0	23.9	32.3	31.0	39.3	34.5
s.d.	6.5	6.4	7.1	7.4	5.9	8.2	6.6
ER-3A with ER3-14 eartips							
mean attenuation	32.3	35.8	37.6	36.6	33.1	39.4	42.5
s.d.	6.4	6.3	5.4	3.5	3.2	3.5	3.4
ER-3A plus Model 3000 earmuffs							
mean attenuation	36.1	45.8	52.5	43.7	35.9	47.8	46.2
s.d.	5.2	5.3	4.6	3.6	4.0	5.0	4.8
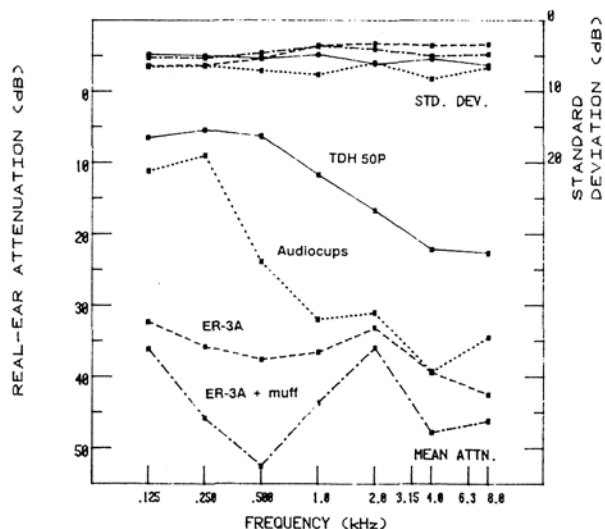
FIG. 3. Attenuation of three audiometric earphones and an earphone-plus-earmuff combination: TDH-50P in MX-41/AR cushion (—); Audiocups with TDH-50P in MX-41/AR cushion (···); ER-3A (---); ER-3A + Model 3000 (-··-).
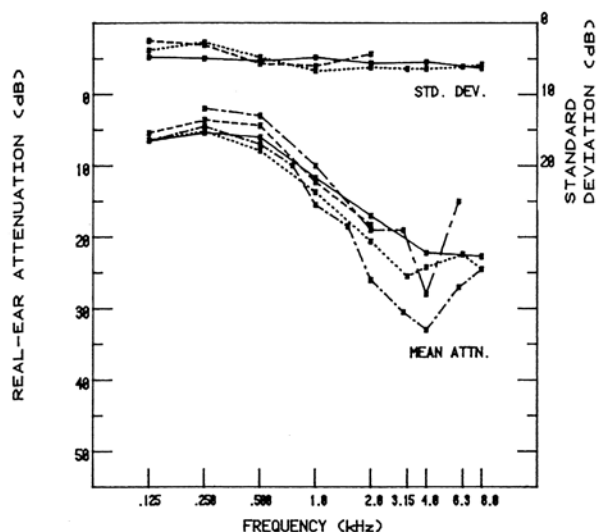
FIG. 4. Five estimates of the attenuation of TDH-type earphones: in MX-4l/AR cushion, this study (—); in Telephonics P/N 51 cushion, from Berger (1982) (···); in MX-4l/AR cushion, from Berger and Kerivan (1983) (---); in MX-4l/AR cushion, from S3.1-1977 (-··-); in MX-4l/AR cushion, from Clark and Roeser (1988) (-- --). Standard deviations not available from the S3.1, and Clark and Roeser data.

B. Threshold shift in noise

Table IV and Figs. 9–11 show the average threshold shift in each of the three noises for the TDH-50P + MX-41/AR, the Audiocups, and the ER-3A earphones, respectively. Recall that the masking noise presented to each subject had been adjusted to effect testing in noise as if each subject had average 500- to 2000-Hz thresholds of 0 dB HL. In Fig. 12, the results are compared across earphones by showing the expected audiogram for a normal-hearing subject being tested in the 54-dBA ENT noise.

Figure 13 shows the correspondence between the 36 calculated and measured values of threshold shift. The solid line depicts a one-to-one relationship, and the dashed lines denote a range of ± 1.5 dB. All but six of the points fall on or
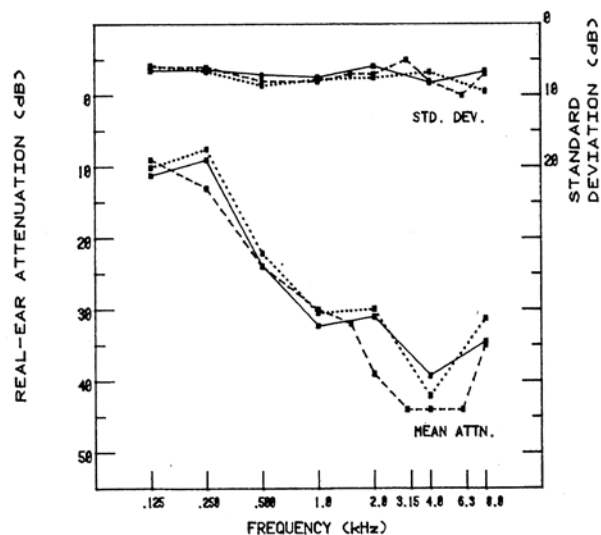

FIG. 5. Attenuation of Audiocups measured by three laboratories: this study (—); Murray and Waugh (1988) (···); manufacturer's data (---).
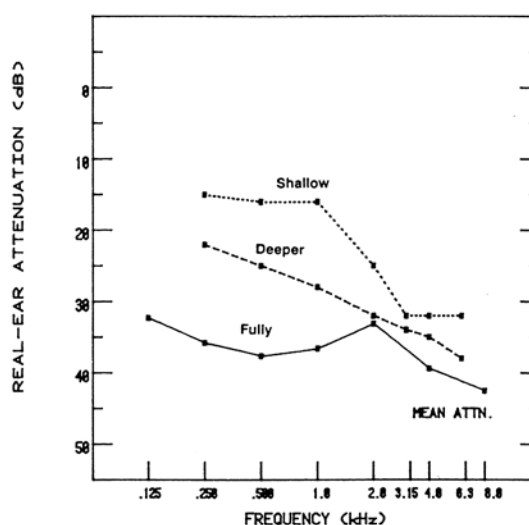

FIG. 6. Attenuation of ER-3A measured by two laboratories: this study, "fully" inserted (—); and Clark and Roeser (1988), "shallow" (···) and "deeper" (---).

within the dashed lines, with no difference between measured and computed values exceeding 4.4 dB. The agreement is surprisingly good considering that, in addition to all of the measurement errors normally associated with a masking experiment, an additional source of variability was present in this study, namely, the specification of the one-third octave-band level of the masking noise. This latter value was a derived quantity, computed from the difference between the measured sound field noise levels and the subjectively determined mean attenuation values of the earphones being tested.

Figure 14 presents an alternative view of the results in terms of the measured masking versus the effective level of the noise. In addition to plotting the results from this experiment, values from two additional experiments utilizing low-
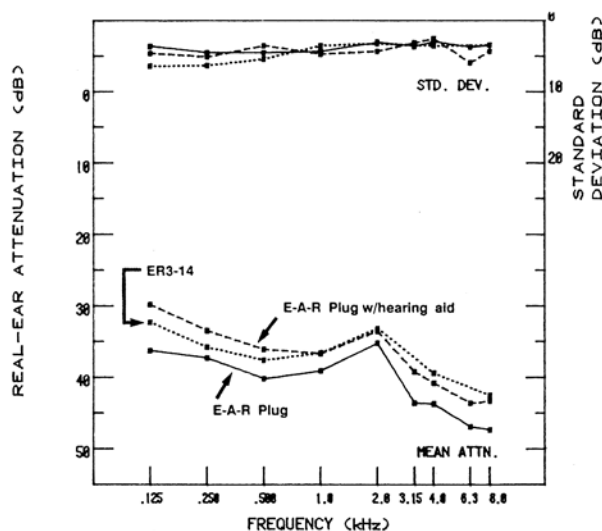

FIG. 7. Attenuation of a standard E-A-R® Plug versus plugs fitted with a centrally located tube and attached transducer: E-A-R Plug (—); ER-3A with ER3-14 eartips (···); E-A-R Plug with tube and behind-the-ear hearing aid (---).
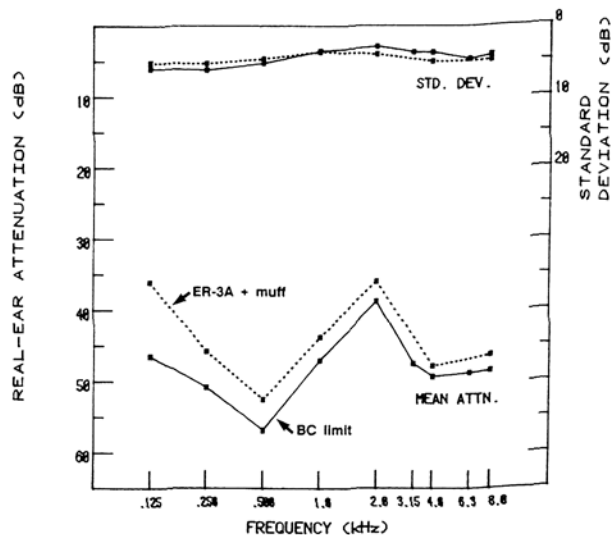
FIG. 8. Attenuation of an insert earphone-plus-earmuff combination (ER-3A + Model 3000) versus the estimated bone-conduction (BC) limits from Berger (1983).

frequency emphasized broadband noises are also included. The data are from footnote 4 of Berger and Kerivan (1983) and from computations based upon data from Waugh (1970) as summarized on p. 1658 of Berger (1986). The solid line is the theoretical relationship based upon the presumption that the apparent internal noise and the external masking noise add on a power-law basis.

Also shown in Fig. 14 is a power curve, fitted to the empirical data using the Marquardt–Levenberg iterative least-squares technique and the following equation:

$$MT = (A)(10)\log[10^{Z/B} + 1.0], \qquad (2)$$

where A and B are unknown constants. The value of 1.0 inside the square brackets was fixed since it controls the y intercept, a value that must approach zero as the effective level (Z) of the noise approaches negative infinity. The solution was found to be $A = 11.7$ and $B = 12.4$, with a coefficient of determination (r^2) of 0.98. Clearly, the fitted curve very closely approaches the theoretical power law (where $A = 10.0$ and $B = 10.0$) and both describe the data with good accuracy.

In the region of an effective level of 0 to -3 dB, the measured masking values fall close to or above the power-law curve depicted in Fig. 14. The data strongly indicate that, in order to achieve a threshold elevation of 1 dB or less, the effective level of the masking noise must be -6 dB or less. This conclusion is in agreement with the early classical studies of French and Steinberg (1947) and Hawkins and Stevens (1950).

III. DISCUSSION

The noise-exclusion data for the three earphones that were tested confirm the expected rank ordering of those devices, demonstrating the relatively poor attenuation furnished by the TDH-type earphones and the successive im-
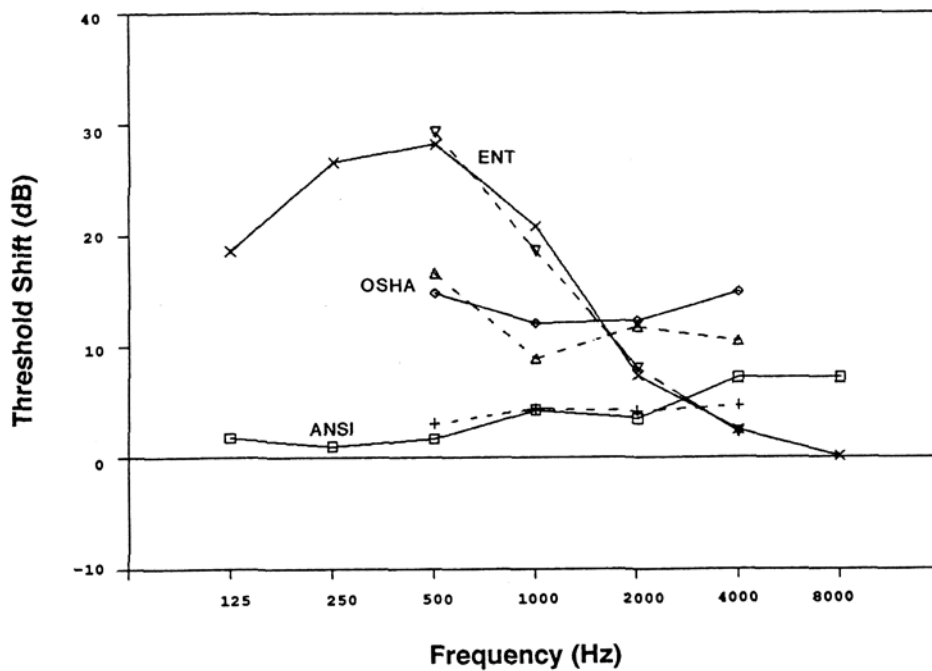
TABLE IV. Masked threshold shifts in noise with three earphones. Values in dB.

Device	Type of noise, shift		125	250	500	1000	2000	4000	8000
TDH-50P + MX-41/AR	ANSI,	measured			3.1	4.4	4.2	4.7	
		calculated	1.6	1.0	1.8[a]	4.2	3.4	7.2	7.3
		measured–calculated			1.3	0.2	0.8	−2.5	
	OSHA,	measured			16.6	8.9	11.8	10.5	
		calculated	7.9	12.4	15.1	12.0	12.1	14.9	9.0
		measured–calculated			1.5	−3.1	−0.3	−4.4	
	ENT,	measured			29.3	18.6	8.1	2.3	
		calculated	18.2	26.6	28.5	20.7	7.2	2.5	0.1
		measured–calculated			0.8	−2.1	0.9	−0.2	
Audiocups	ANSI,	measured			−0.3	0.3	0.4	0.5	
		calculated	0.6	0.5	0.0	0.1	0.2	0.3	1.1
		measured–calculated			−0.3	0.2	0.2	0.2	
	OSHA,	measured			3.8	2.0	3.3	1.7	
		calculated	4.3	9.0	1.8[a]	0.5	2.0[a]	2.0[a]	1.6
		measured–calculated			2.0	1.5	1.3	−0.3	
	ENT,	measured			11.4	4.9	1.6	0.0	
		calculated	13.5	22.9	10.9	3.1	0.7	0.1	0.0
		measured–calculated			0.5	1.8	0.9	−0.1	
ER-3A	ANSI,	measured			0.5	0.3	−0.3	0.7	
		calculated	0.0	0.0	0.0	0.0	0.1	0.3	0.2
		measured–calculated			0.5	0.3	−0.4	0.4	
	OSHA,	measured			0.3	0.6	1.7	2.2	
		calculated	0.1	0.1	0.1	0.2	1.4[a]	2.0[a]	0.3
		measured–calculated			0.2	0.4	0.3	0.2	
	ENT,	measured			2.0	1.5	−0.8	−0.2	
		calculated	0.7	1.5	1.7[a]	1.4[a]	0.4	0.1	0.0
		measured–calculated			0.3	0.1	−1.2	−0.3	

[a] Calculated shifts of 1.8 ± 0.4 dB. The average of these eight calculated values is 1.8 dB and the associated average measured shift is 2.4 dB. See text, Sec. III A.

FIG. 9. Threshold shift in noise with TDH-50P + MX-4l/AR: calculated (—) versus measured (---).

provements in performance that are provided by the Audiocups and the ER-3A. The good agreement between our TDH-type and Audiocup data and the results previously reported in the literature was gratifying. Either our data or the previously reported data for those earphones may be used with little difference in result.

The attenuation provided by the Audiocups is adequate for some testing purposes, although the use of the 17.8-N headband force required to obtain this attenuation does render them quite uncomfortable rather quickly. Furthermore, questions have been raised in the literature concerning the difficulty of properly calibrating and positioning such a device (Morrill, 1986; Murray and Waugh, 1988).

The lack of agreement between the ER-3A attenuation data and the only other values currently reported in the literature was disappointing but understandable. With this type of device, ambient noise attenuation is strongly influenced by insertion depth, even though measured hearing threshold levels are not (Clark and Roeser, 1988). Thus the judgment and skill of the user or experimenter can significantly affect the noise exclusion that is attained. However, even with the worst (i.e., "shallow") insertion of the ER-3A that was reported by Clark and Roeser, they still measured mean attenuation values that were from 6 to 13 dB greater, from 250 to 2000 Hz, than those from the TDH-type earphones, which were also evaluated in their study. (Compare their data for the two types of earphones found in Figs. 4 and 6 of this report.)
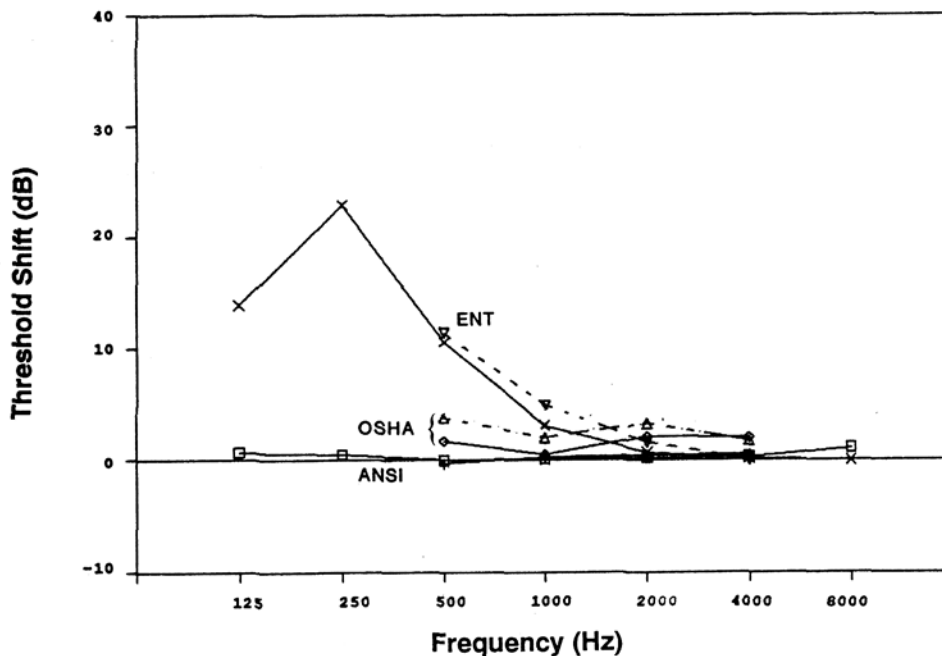

FIG. 10. Threshold shift in noise with Audiocups: calculated (—) versus measured (----).
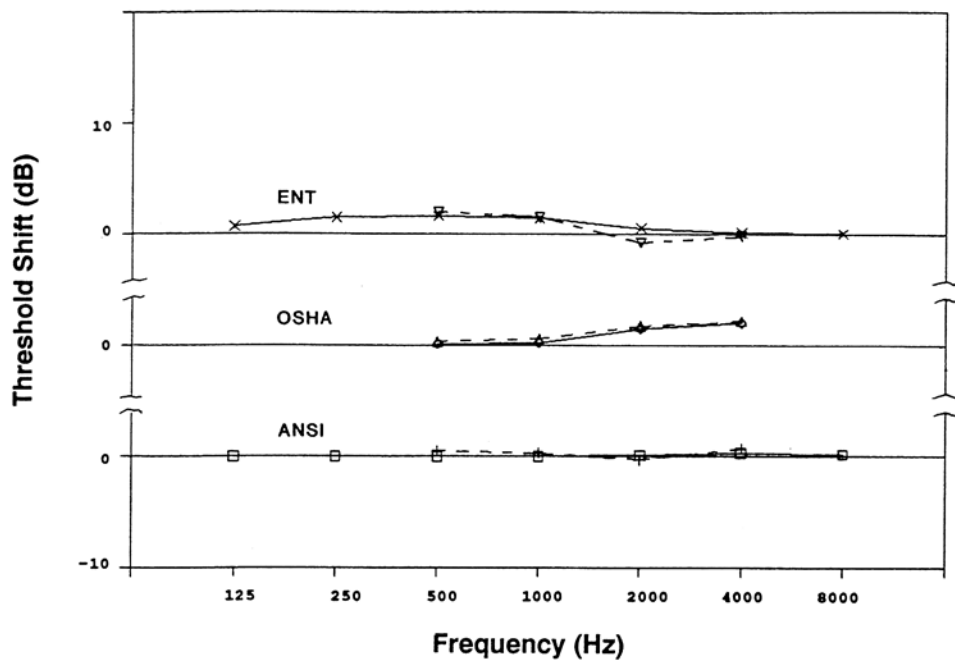
FIG. 11. Threshold shift in noise with ER-3A: calculated (——) versus measured (----).

With respect to our objective of evaluating ANSI (1977) and OSHA (1983) requirements concerning permissible ambient noise during audiometric testing with TDH-type earphones, our answers are clear-cut, and not surprising. Although the ANSI standard has sometimes been criticized as "too stringent to be practical," it was, in fact, based upon accepted data and scientific practice. With the exception of a disagreement we have with the 3-dB correction factor used in that standard (see below), it provides reasonable estimates of permissible noise that, if anything, appear too lenient with respect to its stated 1-dB threshold-elevation criterion. On the other hand, the OSHA levels lead to measured thresholds for those with normal hearing that are elevated by 10 dB or more at most audiometric test frequencies.

A. 3 dB or 6 dB ?

Our suspicion that the use of a 3-dB correction factor in the ANSI standard should result in more than a 1-dB threshold shift appears confirmed in our data (as it had been predicted in the data of others). A noise 3 dB below 0-dB effective masking level (corresponding to the "3-dB correction factor" used in the derivation of the ANSI values) should produce a 1.8-dB threshold shift based on power-law addition. To obtain only a 1-dB shift in the presence of power-law addition, the noise in a "critical band" would have to be 6 dB below the unmasked hearing threshold level (i.e., an effective level of· — 6 dB).

The test of our reasoning is in the correspondence (or lack thereof) between our measured and calculated values. The region near 1.8-dB calculated shift is of particular inter-
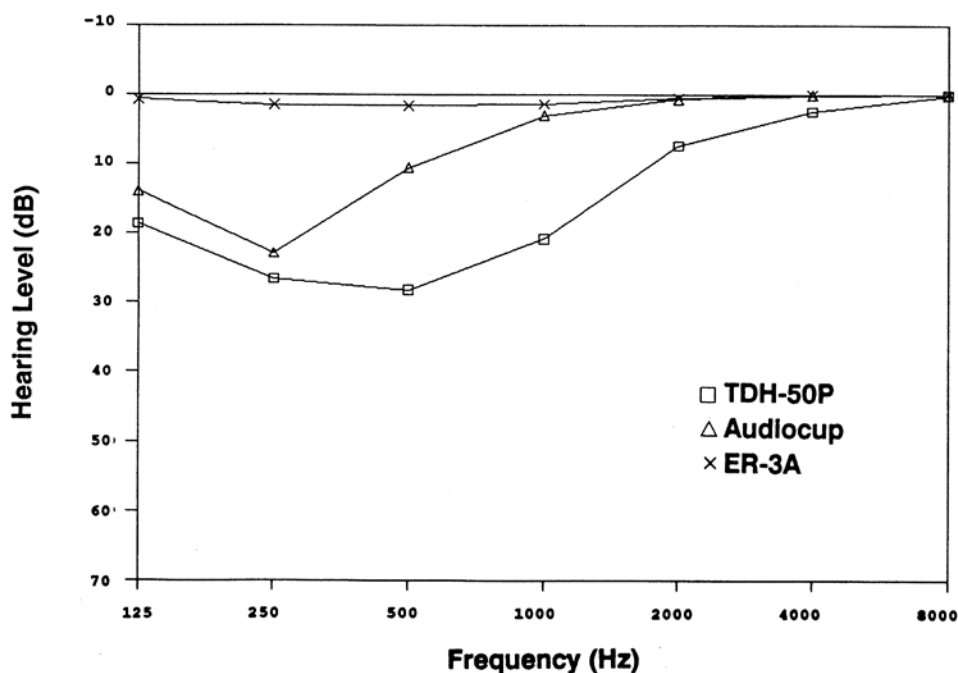

FIG. 12. Expected audiogram in "ENT noise" for a normal subject tested with three different earphones.
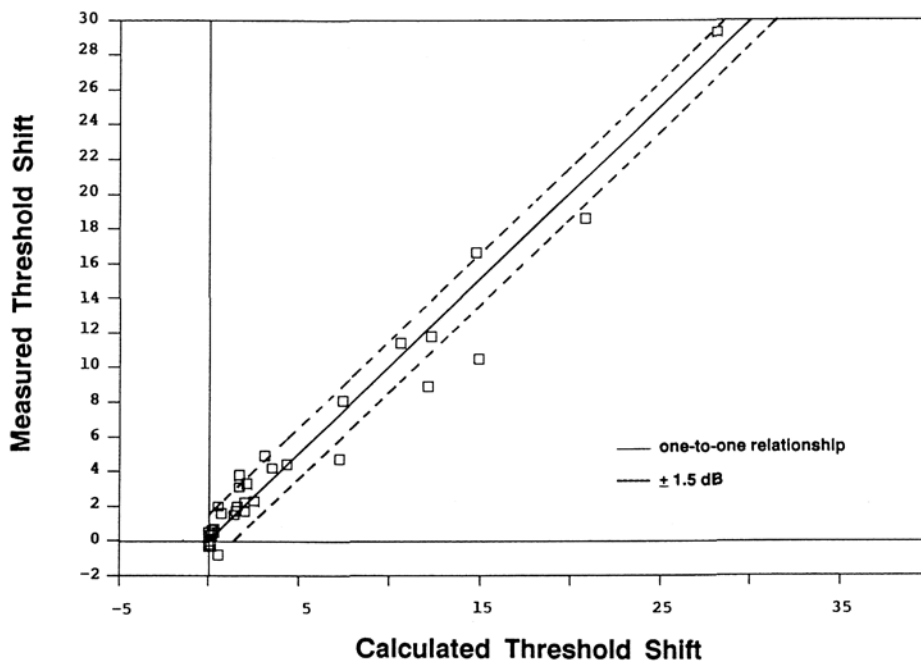
□ TDH-50P
△ Audiocup
× ER-3A

FIG. 13. Measured versus calculated threshold shifts for 36 data points: three earphones × three masking noises × four frequencies. Exact values are listed in Table IV.

est, because the reasoning of the ANSI standard would predict a measured shift of only 1 dB. The average shift that we measured in that region is 2.4 dB, as can be noted by review of Fig. 14 or inspection of the asterisked items in Table IV. In any case, the discrepancies in our experiment between measured and calculated threshold shifts are so small as to indicate that the power law for addition adequately describes the real world of normal hearing.
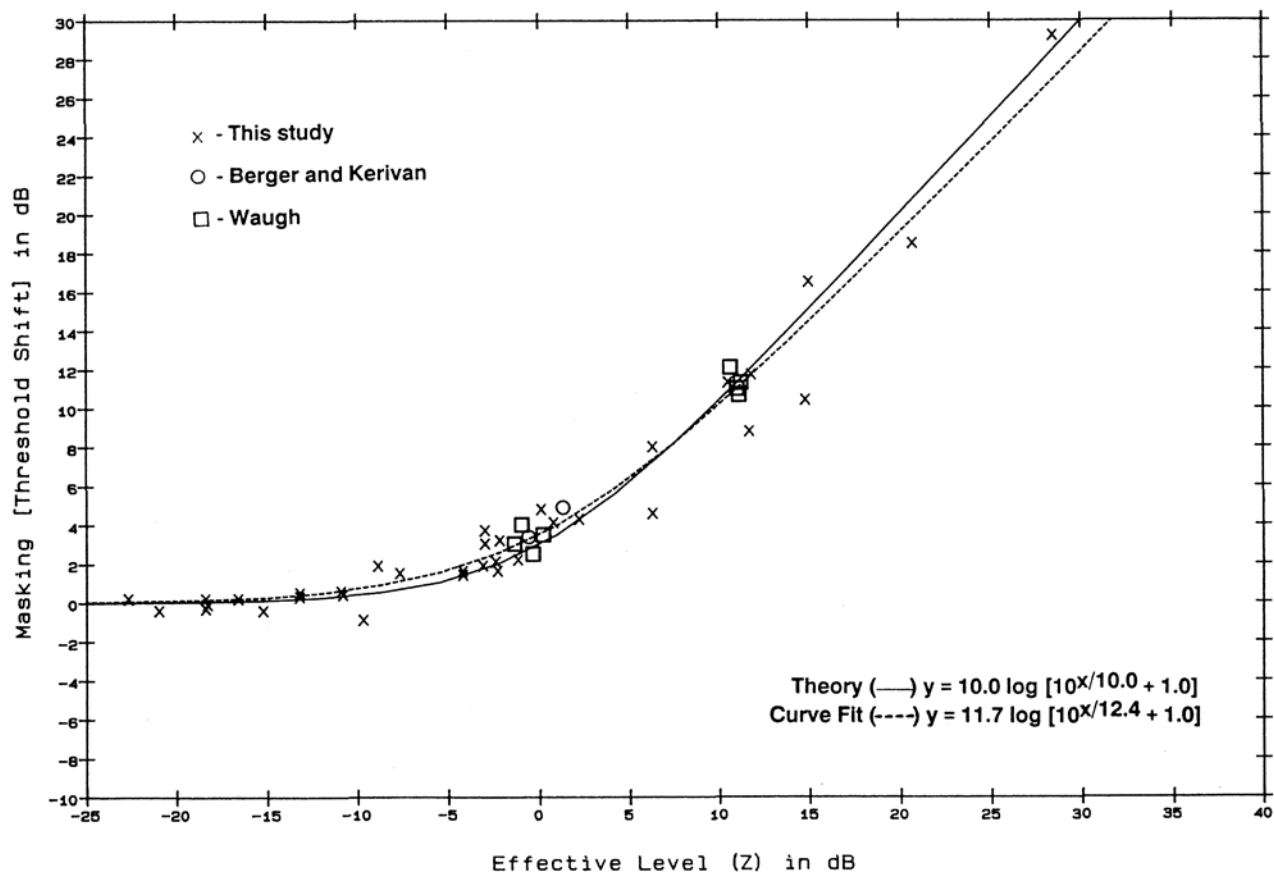

FIG. 14. Relationship between masking (MT) and the effective level (Z) of the masking noise, where $Z = N - (TB - CR) - MAFD$. Data points are experimental values from this study and from Berger and Kerivan (1983; values at 125 and 250 Hz) and Waugh (1970; values at 125, 250, 500, and 1000 Hz). Solid line is the theoretical relationship computed presuming the power-law addition of external masking noise and apparent internal noise. Dashed line is the empirical curve fit using Eq. (2). See text for discussion of unavoidable additional source of variability in the present experiment.

B. Use of the ER-3A in "high" ambient noise levels

Application of ER-3A earphones with properly inserted ER3-14 eartips can be expected to provide 30 to 40 dB of attenuation of ambient noise, a noise reduction sufficient to permit testing to audiometric zero in typical office noise levels. More specifically, we can extend the 1978 Killion and Studebaker recommendations to include the ER-3A as follows.

In ambient noise levels of less than 45 dBA, use of ER-3A earphones with fully (deeply) inserted ER3-14 eartips will, in most instances, allow accurate threshold determination down to an HL of 0 dB over the frequency range of 125–8000 Hz. This criterion should only be applied when no prominent tonal components (whistle, screech, hum, etc.) are audible in the noise. With unusual distributions of the ambient signal spectrum, thresholds in some frequency region(s) may be elevated above those predicted. Should audible whistles, screeches, hums, or tonal-like noise suggest the possibility of such an ambient signal, a more detailed analysis should be performed, or the thresholds of normal-hearing persons should be ascertained in the presence of that signal.

In the preceding paragraph, "accurate threshold determination" is defined as less than or equal to a 2-dB threshold elevation due to masking. This follows from the fact that our recommendations are an extension of Killion and Studebaker's work, which, in turn, was based upon the permissible noise levels specified in ANSI S3.1-1977. As we have shown in this paper, the ANSI levels that were developed using an allowable effective level (Z) of -3 dB lead to a threshold elevation of about 2 dB instead of the 1 dB indicated in the standard. In practice, however, a threshold-elevation criterion of 2 dB provides sufficient audiometric accuracy and is also in keeping with the recommendations of others in the field (Shipton and Robinson, 1975).

It cannot be overemphasized that the above guideline applies only when the ER3-14 eartips are fully inserted according to the manufacturer's instructions. Moreover, although we included a 3-dB safety factor in our adaptation of the Killion and Studebaker recommendations, the 45-dBA figure that we propose was derived using the mean attenuation values for the ER-3A (Table III of this paper). This is the same line of reasoning that was used to develop the allowable ears-covered levels for the MX-41/AR cushions that appear in Table II of ANSI S3.1-1977.

Murray and Waugh (1988) argue persuasively that an allowance for individual variations in the external noise exclusion properties of the earphones should be made; i.e., instead of mean attenuation values, the mean less one standard deviation should be utilized. This is the same type of correction commonly applied to hearing protector attenuation data so that the values utilized reflect the noise reduction that would be expected for approximately 84% of the correctly fitted listeners.

This type of adjustment would reduce our recommendations by approximately 5 dB to an allowable ambient noise level of 40 dBA. Indeed, this would have been our initial recommendation except that the second author argued that it did not seem fair to burden the ER-3A earphone with an apparent performance penalty of 5 dB, compared to the allowable background noise levels for testing with the TDH-type earphones.

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