



**REAT and MIRE Insertion Loss Comparison for Eight
Headphones of Various Passive and ANR Designs,
Inclusive of NRR and Spectral Attenuation**

by

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PROJECT OBJECTIVES

The Auditory Systems Laboratory (ASL) research project addressed the following objectives that were of interest to Shure Corporation:

- 1) Determine, in a head-to-head comparison, whether Shure insert earphone designs, which have passive isolation features, outperform various competitive circumaural and insert designs that incorporate Active Noise Reduction (ANR) circuitry. The performance measures for this evaluation were insertion loss metrics of attenuation performance in 1/3-octave bands and in broadband Noise Reduction Rating (NRR).
- 2) Provide results which will allow Shure to determine how data from NRR-based “subjective” (human listener) methods (i.e., real-ear attenuation at threshold: REAT) and “objective” physical (microphone) methods using the human head as a fixture (i.e., microphone in real ear: MIRE) correlate with Shure’s internal manikin results. One benefit of this objective, according to the Statement of Work (SOW), is to possibly enable Shure to adjust future manikin test results to approximate the results from attenuation tests conducted on a human head. However, due to differences between the human head and any manikin in resonance, impedance, structural conductivity, and other factors, caution is advised in making such approximations. Furthermore, manikins cannot represent the variability characteristic among humans.
- 3) Provide an objective, comprehensive report which describes the instrumentation, facility, protocols, measurements, and analyses, and which include all the head-to-head comparison data in tabular and graphical form. This report, produced by our independent laboratory will enable Shure to publish information concerning its earphones’ performance and to make decisions regarding future earphone design and testing procedures. As Appendix 1 to this final report, the passive attenuation data and the NRR for each product are also provided in standard ASL format reports, one for each product tested.
- 4) Provide data on subjects’ preferences among devices, including their ratings on comfort and other dimensions. These appear in Appendices 3 and 4.

DISCUSSION OF TESTING PROTOCOLS USED

VT-ASL Background and Salient References

Personnel of the Virginia Tech Auditory Systems Laboratory (VT-ASL) have extensive experience in attenuation testing of hearing protectors and earphones/headphones of various passive and electronic (including ANR) types, using many test protocols, including REAT, MIRE, HATS, ATFs, and other techniques. Dr.'s Casali and Robinson developed and published the protocols ASL uses for testing ANR devices (e.g., Casali & Robinson, 1994; 1996), and have tested many devices of that type, both open-back and muff-based, for several corporate and military sponsors. Furthermore, these researchers have published extensively on how augmented hearing protection devices of both passive and electronic varieties should be performance tested, most recently presenting invited and published testimony on the subject at the EPA's Workshop on Hearing Protection in March 2003 (Casali and Robinson, 2003a). A seminal study, which was probably the first objective comparison of REAT versus MIRE measurements, was conducted by VT-ASL, and appeared in *Sound and Vibration* (Casali, Mauney, & Burks, 1995).

To lend explanation and justification to the attenuation measurement protocols that were selected for Shure's research project, a brief overview of different types of attenuation measurements (or in Shure's words, *isolation measurements*) is presented next.

Insertion Loss (IL) versus Noise Reduction (NR)

To understand how hearing protection devices (HPDs), as well as similar devices including in-ear monitors, communications headsets, and custom-molded ear couplers are tested and rated as to their attenuation performance, it is first necessary to cover the basics of laboratory attenuation measurement techniques. (Hereafter, for simplicity, all of the aforementioned devices will be collectively referred to as *ear isolation devices, or EIDs*) While almost all measurement techniques are applicable to conventional, passive EIDs, some of these techniques are amenable to certain electronic EIDs but not others. When attenuation performance is quantified using microphone-based (*i.e., physical*) measurements, two approaches are commonly used. In both cases, two distinct measurements are needed to quantify the performance of the EID; one to indicate the noise level to which the wearer would be exposed *if the EID were not worn* and the other to indicate the noise level to which the wearer would be exposed *if the EID were worn*. The two approaches differ in the number of microphones used to perform the measurements, the locations of the microphones, and the time sequence of the measurements. It is important to recognize that the two approaches typically produce different attenuation values.

The first of these methods is referred to as *insertion loss* (IL), wherein a single stationary microphone is used and two measurements are performed, one with the EID in place and one without the EID present. The *attenuation* is the difference between the two measurements, hence the phrase *insertion loss*, which is the reduction (or loss) in the noise level after the insertion of a barrier (the EID) between the noise source and the measurement location. In Figure 1, this would be represented by the difference in the levels measured at locations A and A' (IL = A – A'). The microphone can be located in an acoustical test fixture or in the concha or ear canal of a human test subject or acoustical manikin. As will be discussed below, because real-ear attenuation at threshold (REAT) test procedures also represent two distinct threshold measurements performed at different times with and without an EID in place, they are also referred to as insertion loss measurements. The REAT test is therefore a measure of insertion loss, and is computed as: Occluded Threshold in dB – Unoccluded Threshold in dB (essentially, A' – A, where the subject's ear replaces the microphone).

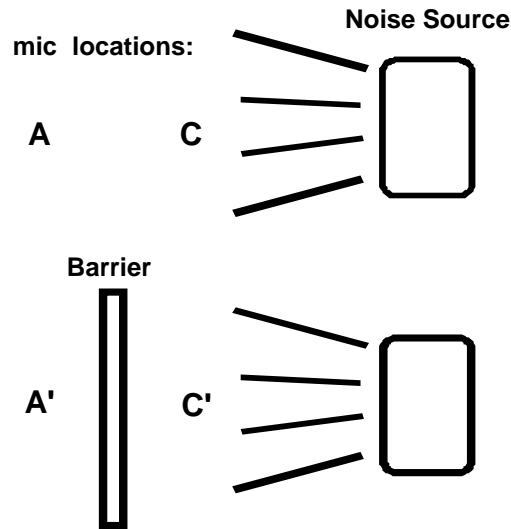


Figure 1. Microphone locations for *noise reduction* (NR), $C' - A'$, and *insertion loss* (IL), $A - A'$, measurements of attenuation. All measurements are microphone-based and in dB.

Noise reduction (NR), on the other hand, utilizes two microphones with the measurements made *simultaneously* on the interior and exterior of the HPD. This would be represented by the difference in the levels measured at locations A' and C' in Figure 1 ($NR = C' - A'$). As with IL, NR measurements may be made using test fixtures, manikins, or human subjects. If human subjects are used, the measurements obtained at C' must be corrected for the transfer function of the open ear (TFOE; Casali, Mauney, & Burks, 1995).

Real-Ear Attenuation at Threshold (REAT)

Most hearing protector attenuation data (and all attenuation data required for EPA labeling purposes when an EID of any type is claimed to provide hearing protection) are obtained using human subjects in a binaural threshold shift methodology referred to as Real-Ear Attenuation at Threshold (REAT). (Because this procedure relies on humans as the “transducers,” this procedure is often incorrectly referred to as a *subjective* procedure, but a more appropriate term is *psychophysical* procedure.) As implemented in the current hearing protection test standards of the American National Standards Institute (ANSI S3.19-1974 [EPA-required] and ANSI S12.6-1997), subjects track their thresholds for 1/3-octave bands of noise (at center frequencies of 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz) with and without a hearing protector in place. The difference between the two thresholds (the threshold shift due to the presence of the EID) represents the insertion loss of the hearing protector. The mean and standard deviations of the 10 subjects’ attenuation values across the spectral bands are used to compute a single-number Noise Reduction Rating (NRR) in dB, which is part of the EPA-required label (CFR, 2002) and is intended to be used in computing the estimated protected exposure level under the protector when used in a given noise environment measured in dBC. (See Casali and Robinson, 2003b or the reports of Appendix 1 for NRR computational procedures.) This REAT methodology is recognized as the most accurate method available in that it can account for individual differences in the fit of the devices across the subject sample as well as the human bone conduction effect, which, as a flanking path, constitutes the ultimate limiting factor in EID attenuation. However, there are also disadvantages associated with REAT, including: slight overestimation of the low-frequency attenuation of EIDs due to physiological noise (due to the fact that the EID enhances low frequency bone conduction, resulting in slightly inflated occluded thresholds), inter- and intra-subject variability, and the need for extremely quiet test environments. REAT cannot be used to assess certain augmented EID technologies (e.g., ANR EIDs which cancel noise through destructive superposition effects, and nonlinear devices which increase attenuation as a function of incident noise level). At least for hearing protective devices, this is a major problem with the current EPA labeling requirement (CFR, 2002), in that it requires data from the ANSI S3.19-1974 standard, which does not accommodate certain augmentations for hearing protection devices or EIDs. Thus, these devices cannot be properly labeled as to their full range of performance in certain noise environments; in other words, they can only be measured by REAT for their passive attenuation with the electronics turned off.

ANSI S3.19-1974, specifically the Experimenter-Fit protocol alternative, is currently required by the EPA for hearing protection labeling purposes per CFR (2002). However, there has been recent support from various hearing conservation groups in the U.S. (e.g., the National Hearing Conservation Association) for replacement of the aforementioned standard with the newer

ANSI S12.6-1997, using the Method B Subject-Fit protocol, for HPD labeling purposes. Nonetheless, it appears that adoption of a newer standard into federal law is at least 2-3 years away, and as such, ANSI S3.19-1974 is still the standard in force for attenuation measurements. In the Shure research, this REAT standard was applied to all 8 products using the Experimenter-Fit protocol and the required panel of 10 qualified subjects. This enables Shure to compare its products with competitors' products on an NRR and spectral attenuation basis, and allows Shure to label its products under the EPA regulation for provision of hearing protection, if so desired at a future time.

Microphone in Real-Ear (MIRE)

The microphone-based counterpart to REAT is Microphone in Real-Ear (MIRE). This methodology is standardized in ANSI S12.42-1995 and MIL-STD-912 and is referred to as *objective or physical* since the measurements are microphone-based. As the name implies, small microphones (connected to a spectrum analyzer) are placed in human subjects' ears (at or near the opening of the ear canal) and insertion loss measurements are performed using relatively high levels of a broadband noise stimulus (usually pink or white noise) with and without the EID present. This procedure is easily implemented with earmuffs and some supra-aural devices, but is more difficult to implement with earplugs or semi-insert devices due to the need for wires running underneath the eartips, which can break the seal. Also, it is difficult, if not impossible, to ensure that the microphone remains in the same position and orientation during the occluded trial as in the unoccluded trial. (Both of these problems were encountered with the Sony NC-11 insert-type device and, as such, MIRE data could not be obtained).

Another problem with insert-type EIDs is that in the open-ear condition, the human subject is unprotected during the measurement, and if the device's attenuation is high enough (as expected with several of the current products) to necessitate that the excitation noise be about 95 dB (note that the level must be equivalent for the open-ear and occluded measurements), this can create a potential hazard for the subject if exposures are sustained. (This is not a problem with muff-type EIDs since a protective earplug can be worn by the subject in *both* the open-ear and occluded conditions, affecting neither measurement.)

Advantages of MIRE testing are that the results are not contaminated by physiological noise as are REAT results, the process is somewhat quicker than REAT testing, and since the measurements are performed at elevated noise levels, there is no requirement for extremely quiet ambient noise conditions. Also, because real human heads are used as test fixtures, MIRE measurements can still account for individual differences in the fit of the devices across the subject sample just as REAT measurements do. However, MIRE measurements cannot account for true bone conduction effects (and thus may overestimate

attenuation at mid-to-higher frequencies) and also require special equipment (miniature microphones, microphone power supplies, spectrum analyzer, etc.). In the Shure research, the MIRE procedure was applied to only those 3 products which have ANR circuitry in their design (again, MIRE measurements were not possible for the Sony NC-11, the fourth device, although repeated attempts were made with the smallest Knowles microphones), and it was applied to these products specifically to determine the increment (or decrement) in attenuation which results when the electronics are turned on. To reduce variance and to afford comparisons against the passive devices, an Experimenter-Fit protocol and the same panel of 10 subjects were used as in the REAT tests. Essentially, for each passive device, the REAT attenuation was obtained, but not MIRE, since MIRE cannot properly be used with deeply inserted EIDs (such as foam-tipped devices) because their high passive attenuation necessitates that high levels of pink noise be used which is not safe for the unprotected subject in the open-ear condition, and also since deep insertion of a MIRE microphone is impossible on most subjects. (Shallow microphone insertion would disadvantage insert-type products since it would inhibit the proper insertion of the noise-isolating eartips.) For ANR-based devices, the collection of the ANR attenuation component via MIRE along with the passive attenuation by REAT enables Shure to compare its products' REAT passive attenuation with the REAT passive attenuation of the ANR products, and then add-on the ANR attenuation component to ascertain whether it constitutes a significant advantage.

Obtaining the ANR component from MIRE. As mentioned above, standardized attenuation data and NRR ratings are not available for ANR hearing protectors or headsets in part because the EPA-required testing standard (ANSI S3.19-1974) does not accommodate them. But MIRE testing can be used effectively, per ANSI S12.42-1995, or similarly, MIL-STD-912 to measure the passive (ANR off) and total (ANR on) IL of the device, and then algebraically one can compute the ANR component of IL. By measuring two occluded (protected) states, one with ANR on and one with ANR off, the need to expose an unprotected subject is obviated. The *active component* of the attenuation is then computed using the following equation:

$$[\text{Active ANR component of IL} = \text{MIRE total IL} - \text{MIRE passive IL}]$$

REAT or MIRE testing were used to quantify the passive component of the total attenuation (and both will be applied in the Shure research for ANR devices), but the choice of method can affect the data. MIRE attenuation at low frequencies is typically slightly lower than REAT attenuation due to the physiological noise masking effects on occluded thresholds that occur in REAT testing. Looked at in another way, it could be said that REAT overestimates the low frequency attenuation of HPDs. In addition, MIRE, unlike REAT, does not account for the bone conduction path so it possibly overestimates attenuation in mid-frequencies. Finally, with ANR devices, it should be noted that passive attenuation is often decreased in the mid-frequencies (from about 1000 - 3000

Hz) when the ANR circuit is turned on (i.e., the electronics produces its own and/or amplifies incident noise which increases the measured levels under the device), and this effect is accurately accounted for by the MIRE formula shown above.

EXPERIMENTAL PROTOCOL

Investigators

Dr. Jeff Lancaster, Research Assistant Professor and VT-ASL Manager, and Dr. Gary Robinson (formerly of the ASL) served as experimenters for all tests. Dr. John Casali was responsible for supervising the project, designing the evaluation protocols, and overseeing report preparation. He is Grado Professor and Founder/Director of the VT-ASL, has published over 130 papers on hearing protection and ergonomics issues, and has acquired and directed over 70 research contracts, the vast majority of which are related to hearing protection and communications devices. Approximately 20 of these contracts are related to the performance (comprising attenuation, speech intelligibility, and signal detection performance), of ANR hearing protectors and headsets. In the Auditory Systems Laboratory at Virginia Tech, a manufacturer-independent facility which is part of a state university, Dr. Casali has pioneered testing protocols for ANR and other electronic hearing protection devices. In the course of this work, he has been involved with ANSI standards development and EPA labeling issues for hearing protection, including electronic devices. Dr. Lancaster, a member of the ASL since 2001, has served as experimenter for hundreds of human subject tests of hearing protector attenuation.

Worktask Sequence and Schedule

Following is the itemized experimental plan used in this project with the milestones for each task completed shown in parentheses. This timeline is given in the form of “days or weeks after contract award” since it was not known how quickly Shure and Virginia Tech’s Office of Sponsored Programs could complete a signed project award. Every effort was made to hold to the timeline milestone for each task, and to be timely in presentation of the data to Shure in both electronic and printed form. At the point of submission of this report, and the electronic provision of data prior to it, the project is within schedule and budget.

- 1) Contract was awarded by Shure and finalized with VT Office of Sponsored Programs. (*Awarded 5/28/04.*)
- 2) Competitor’s devices (for which the costs and shipping were unknown at time of proposal) were ordered by VT-ASL outside the contract budget. Reimbursement for products and shipping will be provided by Shure on an actual cost basis, and billing for these items will follow. Shure supplied its

- own products for testing. (*Ordering occurred within 3 days of contract award.*)
- 3) Final details regarding experimental protocols discussed herein were finalized by phone conference between Shure and VT-ASL. (*Completed within 1 week of contract award.*)
 - 4) Laboratory instrumentation setup and calibration was performed at VT-ASL. (*Standard instrumentation used was already in place; a repeat calibration was performed before experimental trials.*) Approval from the University Institutional Review Board on human subjects was obtained. (*Begun upon verbal approval of contract and completed prior to receipt of products for testing.*)
 - 5) Shure personnel were invited and visited VT-ASL to witness instrumentation of human subjects, audiometric procedures, and sample experimental protocols. Shure personnel served as test subjects as desired. Due to VT-ASL's quality assurance procedures, Shure personnel were not present in lab during actual product testing -- this ensured that no questions about objectivity of tests could result (Hankins, Robinson, & Casali, 2000). (*Visit occurred, and was over two weeks prior to testing.*)
 - 6) Data collection for REAT and MIRE testing on all 8 products. (*Completed within 6 weeks following receipt of products for testing - Item 2; all products were received before testing commenced to allow for counterbalancing of product order to obviate any bias due to order or subject familiarization across multiple tests.*)
 - 7) Data reduction/analysis and development of tables and graphs in electronic form for provision to Shure. (*Within 1 week after completion of data collection - Item 6.*)
 - 8) Final report prepared in printed form and supplied to Shure. (This is a comprehensive report covering all aspects of the experiment, inclusive of all data in tabular form and spectral graphs of attenuation.) (*Within 3 weeks after completion of data collection - Item 6.*)
 - 9) Follow-up discussions with Shure, and/or if Shure personnel desire, a visit to Shure to discuss results, at Shure's travel expense. (*This will occur at Shure's discretion.*)

Experimentation

Experimental design. Attenuation data, via the above-described insertion loss paradigm, was collected using both MIRE and REAT procedures as shown in the experimental design depicted in Figure 2 on page 10. Subject assignment to test condition is shown in the cells, and to the extent possible during the experimental tests, presentation order of EID products was randomized across subjects to avoid the aforementioned bias potential of ordering or learning effects. As shown in the block design of Figure 2, **REAT** methodology, per ANSI S3.19-1974 - Experimenter-Fit, was applied to obtain the *passive* attenuation on all 8 products, using the same set of human subjects on all products. This 10-subject protocol afforded several advantages:

- 1) It yielded data for computation of the NRR as well as mean and standard deviation statistics of spectral attenuation for all devices, providing a standardized basis for comparison of products as to their passive attenuation;
- 2) Use of a homogeneous subject sample so that subject differences were controlled for across products (the same subjects were recruited for the MIRE tests for the same reason); and,
- 3) Use of Experimenter-Fit reduces the variance in the data that is known to occur when subjects are tasked with fitting EIDs on themselves; this reduced quality of fit as an uncontrolled source of variance when comparing the REAT passive and MIRE ANR-component attenuation data. With respect to this issue, having subjects fit the products on themselves particularly disadvantages the insert-type devices (characteristic of both the Shure and Sony devices), which are typically more difficult to don properly than a circumaural earmuff-based device. (This is known from experience with hundreds of different products that have been evaluated in the VT-ASL, e.g., as exemplified by Casali & Park, 1991, Casali & Epps, 1986; and Casali & Lam, 1986).

REAT data was obtained and reported in 1/3 octave bands centered at 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz as specified by ANSI S3.19.1974 and CFR (2002).

As shown in the experimental design of Figure 2, **MIRE** data was collected on 3 of the competitive products for the sole purpose of obtaining the ANR component of attenuation, which, as explained in the previous section entitled “Discussion of Testing Protocols to be Used,” cannot be achieved using REAT tests. Note that the Sony NC-11 product was not tested using MIRE due to an inability to standardize microphone placement position between and within subjects. Again, as with the REAT protocol, each EID was optimally fit by the experimenter on each of the 10 subjects in the MIRE tests. MIRE testing was conducted per ANSI S12.42-1995 to measure occluded sound levels under the EIDs for both the passive (ANR off) and total (ANR on) configurations of each device. Then the *active ANR component* of the attenuation was computed using the following formula:

$$[\text{Active ANR component of IL} = \text{MIRE total IL} - \text{MIRE passive IL}]$$

MIRE data was obtained and reported in all adjacent 1/3 octave bands centered from 63 Hz to 16,000 Hz.

S1-10	N/A	
S1-10	S1-10	SONY MDR-NC11 (ANR)
S1-10	S1-10	SONY MDR-NC20 (ANR)
S1-10	S1-10	SENNHEISER PXC-250 (ANR)
S1-10	N/A	BOSE QUIET-COMFORT 2 (ANR)
S1-10	N/A	SHURE E3c w/foam sleeve
S1-10	N/A	SHURE E3c w/silicone rubber sleeve
S1-10	N/A	SHURE E2c w/foam sleeve
S1-10	N/A	SHURE E2c w/PVC flex sleeve
S1-10	N/A	

REAT	MIRE
Listeners	Human
125-8000 Hz	Head
	63-16000 Hz

Figure 2. Experimental design, with human subject assignment shown in cells, for REAT and MIRE attenuation data collection.

Subject screening protocol. Each of 15 subjects was recruited for participation in both the REAT and MIRE tests. Although only 10 subjects were actually required, an extra 5 were recruited to ensure that replacement subjects were immediately available should unforeseen attrition occur. All subjects were drawn from a known, pre-qualified population maintained by VT-ASL. In a qualification session lasting approximately 1.5 hours, subjects completed the following procedures: 1) experiment description and informed consent, 2) otoscopic examination, 3) pure-tone audiometry (using a Beltone 114 clinical audiometer), requiring hearing threshold levels no greater than 20 dBHL at 125, 250,

500,1000, 2000, 3000, 4000, 6000, and 8000 Hz, and 4) 1/3-octave band open ear threshold variability tests, over a minimum of 5 trials at each test band, to establish a range of trial-to-trial variability on 3 consecutive trials of not greater than 6 dB using modified Békésy tracking (with reliability checks and computer scoring) that was used in the experimental trials.

Subjects read and signed an informed consent document as per the requirements of the Virginia Tech Institutional Review Board for Human Subjects in Research. The aforementioned qualification tests, governed by the VT-ASL's quality assurance manual (Hankins, Robinson, & Casali, 2000) more than meet the requirements of ANSI S3.19-1974 or any other U.S. standard for REAT protocols.

Experimental protocol. Subjects returned to the VT-ASL for a total of 8 sessions in which one product was tested during each session. For all 8 products, REAT insertion loss data was collected in the session. For the ANR-based products, MIRE insertion loss data was collected following the REAT data. For each EID product, 3 separate fittings of the device were made, producing 3 REAT threshold trials (thus 3 attenuation values) for each subject at each test frequency. Likewise, 3 separate fittings were obtained for each product on each subject for the MIRE tests. Again, these multiple trials provided a measure of within-subject variability for each product, and yielded a better statistical basis for device performance. Standard deviations were computed, as this was necessary for calculation of the NRR. Each experimental session took approximately 1.5 to 2 hours.

It is important to note why each fitting was performed by the experimenter and not the subject. Experimenter-fit represents an effort to obtain an "optimal" seal and reduce extraneous measurement differences that would result from variance in fits. In other words, the basic objective was to measure attenuation differences that were *due to differences in EID product design*, and this question was best answered if all products were fit in as homogeneous a manner as possible. Experimenter-fit best achieves this, and furthermore, it also adhered to the EPA's (CFR, 2002) required protocol for device attenuation testing and labeling per ANSI S3.19.1974.

At the end of the 8th product session (after all products had been experienced during the 8 sessions of tests), the subject was presented with all 8 products at once for inspection, fitting on themselves, and a subjective comparison. Subjects ranked the devices from 1 to 8 as to their preference for comfort and quality/ease of fit. Of course, this preference ranking data, as with the attenuation data, remains confidential to Shure. It constitutes a no-charge side benefit to the major objective of obtaining attenuation data for comparison across products. These comfort data appear in Appendix 3.

Comfort rating data was also obtained for each device at the end of the session wherein that device was tested. The ratings were made using a multi-dimensional Likert-type survey. This survey, and the data obtained therefrom, appears in Appendix 4.

Experimental facility, sound field/stimuli, instrumentation. All equipment and instrumentation necessary to conduct the experiments currently resides in the VT-ASL. This lab occupies over 2500 ft² in Whittemore Hall on the Virginia Tech campus. Two sound chambers (an anechoic chamber and a reverberant room) are housed within a larger sound-isolated room with double exterior walls and an acoustic door. A Norwegian-Electronics 828 Hearing Protector Test System was configured to present 3 channels of uncorrelated sound sources in the reverberant room (one in each of 3 planes). A detailed overview of this facility appears at website: http://filebox.vt.edu/eng/ise/casali/audio_lab.pdf

All data was obtained in the reverberant room of the VT-ASL, which met all requirements of both ANSI S3.19.1974 for REAT and ANSI S12.42-1995 for MIRE. Instrumentation for presentation of the pink noise for MIRE and 1/3-octave band test signals for REAT included an IBM PC with custom software which was interfaced with and controls the Norwegian-Electronics 828 Hearing Protector Test System. Three channels of uncorrelated sound sources were presented through a set of 3 frequency-response-matched TEP-2 loudspeakers, one in each room plane. This achieved a uniform, random-incidence, diffuse sound field about the head center position for both pink noise (for MIRE) as well as 1/3-octave stimuli (for REAT). All calibration data for the reverberant room and test system appear in Casali, Robinson, & Hankins (2000).

REAT tests were conducted using a variant of Békésy tracking, which incorporates computer software-imposed safeguards to achieve validity and reliability of threshold. Subjects tracked their hearing thresholds to the 1/3-octave band stimuli using a silent hand switch, and were allowed to advance to the next frequency band only after meeting certain waveform criteria. All thresholds were computer-scored and recorded on disk. The threshold pairs for open-ear and occluded-ear thresholds at each frequency band were then differenced to obtain the insertion loss for that frequency band on a given trial.

MIRE tests followed the REAT tests on each ANR product. MIRE tests were conducted using a pink noise (flat-by-octaves), also generated by the 828 test system. The level of the stimulus noise was at least 10 dB above the level measured *under* an optimally-sealed double-wall high attenuation earmuff (NRR of 29) to ensure that there was sufficient signal headroom to accommodate the attenuation provided by all of the devices under study (per ANSI S12.42-1995). From prior lab experience, this pink noise level was set at 95 dBA, and it was maintained constant across all EID products under test. To allow equitable comparison among products, a common microphone (Knowles model 3132) and measurement instrumentation (Larson-Davis 3200 1/3-octave band spectrum

analyzer) was used. For ANR-based EIDs of the circumaural (Bose Quiet Comfort 2) or semi-circumaural, (Sennheiser PXC-250; Sony MDR-NC-20) types, placement of the measurement microphone was either in the concha held by double-sided tape, as shown in Figure 3. For the insert-type Sony MDR-NC-11, an even smaller microphone (Knowles model FG-3652-P16) could not be mounted inside the ear canal in such a way as to ensure standardization of fit of the eartip and of the orientation/position of the microphone; as a result, this device was not tested using the MIRE procedure (as indicated above).

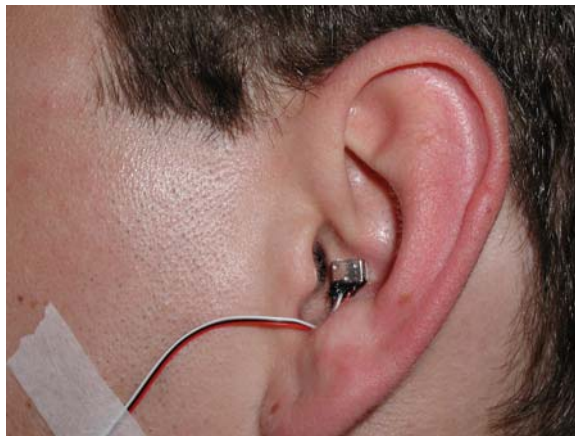


Figure 3. Microphone placement on floor of concha, as used for MIRE measurement of ANR earphone/headphone attenuation.

RESULTS

Appendices for Complete Attenuation Data

Herein, a summary of REAT and MIRE insertion loss data is provided via the use of graphs. The complete spectral attenuation data set is simply too voluminous to present in reasonable fashion in printed tables. Therefore, accompanying this report as Appendix 1 is a CD that contains, for each device tested, a Microsoft Excel Table that displays MIRE and REAT 1/3-octave band data for each trial of 10 subjects, as well as mean results at the bottom of each table. Likewise, as Appendix 2 to this report, a complete NRR and spectral attenuation report (for the passive data only) is provided for each device, in the ASL's standard format for such reports.

Preface on Graphical Results and Descriptions Therefrom

It is important to note that the graphical results presented below are summary plots of the tabled data given in Appendices 1 and 2. The prose discussion following the graphs, being directly attributable to those graphs, should not be reported elsewhere without the supporting graphs. This prose represents the experimenter's interpretation of the graphs; however, for any publication purposes, the graphs must be presented.

REAT Results: All Devices

The REAT passive attenuation results for all tested devices are displayed in Figure 4. What is immediately notable is the increased attenuation afforded by the Shure devices, especially the E3c, when using the foam seal instead of the flanged seal. Using the foam seal, the E3c's attenuation qualities were superior to all other devices tested, with some overlap with the E2c (again, with the foam seal) in the high frequencies (i.e., above 6300 Hz). Calculated NRRs for the E3c foam and flanged devices were 25 and 18, respectively (see Figure 5). Calculated NRRs for the E2c foam and flanged devices were 17 and 15, respectively, as shown in Figure 5. The E3c's design, when compared with the E2c's design, fostered ease of fit into the ear canal opening, which was not as problematic as was the E2c's larger earphone design. The E2c's physically larger structure may have affected fit and/or attenuation because most of its body (and thus weight) resided in the concha, outside of the ear canal opening (where the flange or foam seal was made)—unlike the smaller E3c, which was much smaller and lighter. Again, these results occurred with an expert experimenter rolling down the foam and properly fitting it. Whether a subject could achieve this quality of fit is doubtful.

In contrast, the supra-aural design and positioning of the Sennheiser product resulted in attenuation values that were much less (on average) than most of the other products tested, as would be expected. The 'on the ear' position of the Sennheiser product presented several avenues for noise to reach the tympanum (e.g., at any point on the circumference of the headphone pad).

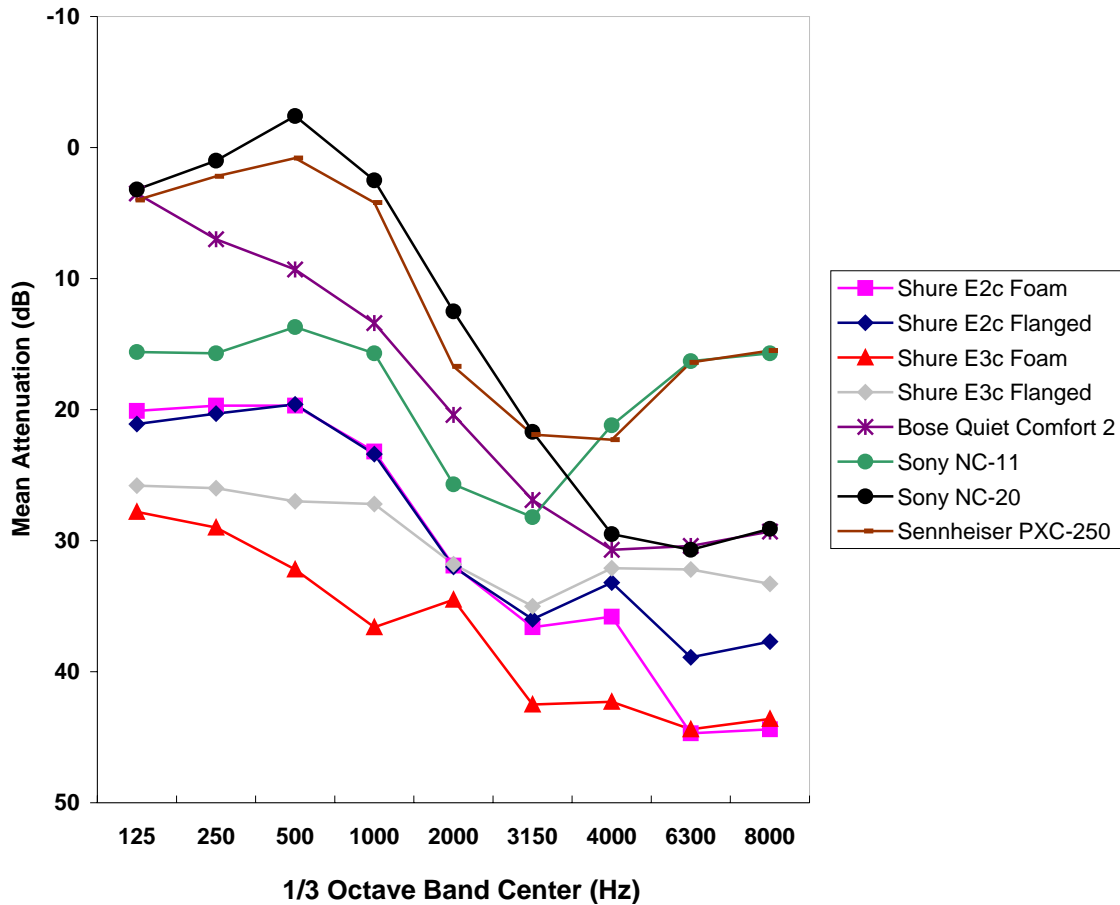


Figure 4. REAT passive attenuation data for all devices.

As such, very little passive attenuation was afforded this product, even at the mid- to high frequencies. It could be that the observed variability in participants' thresholds resulted in negative attenuation values due to the weak passive attenuation of the design, which impacted the Sennheiser's calculated NRR value of -3. The Bose product, which used a circumaural design, resulted in improved attenuation that generally increased with frequency, with some leveling off at the higher frequencies, resulting in a calculated NRR of 6. However, the Sony NC-20 product, which also used a circumaural design, fared the worst of all tested devices in passive performance, with a calculated NRR of -7. Similar to the Sennheiser product, the lower passive attenuating qualities of the NC-20, especially at the low frequencies, resulted in some negative thresholds during the REAT test. It could be that the design of the earcup itself, which included 'holes' on its outside surface, may have resulted in decreased attenuation when compared to the more solid and uniform design of the Bose product's earcup. The Sony NC-11's design included a flanged ear canal plug attached to a large headphone stem that hung down from the ear opening. This design resulted in relatively high attenuation values between about 2000-3150 Hz, with somewhat flat attenuation below and above those frequencies. The decreased attenuation

measured at the higher frequencies (wherein passive attenuators typically perform best [i.e., 4000-6000 Hz]) when using the NC-11 resulted in a relatively low NRR score of 0, which connotes no measurable attenuating benefit in their use. Again, see Figure 5, which provides all NRR data, with details appearing in Appendix 2.

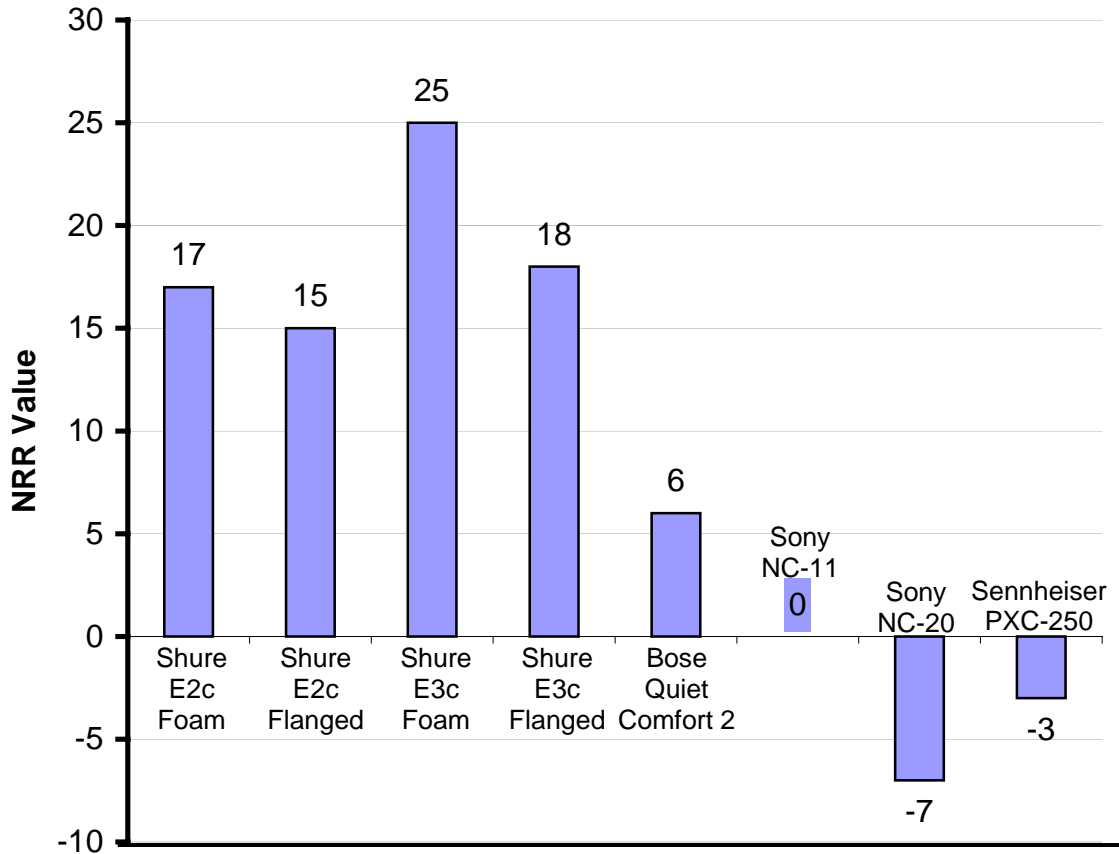


Figure 5. Noise Reduction Rating (NRR) of passive attenuation for all devices (supporting spectral data and computations appear in Appendix 2).

MIRE Results: Sony NC-20, Sennheiser PXC-250, and Bose QC-2

Comparison of REAT data with MIRE data can be misleading. While REAT data using human subjects was a measure of perceived (i.e., subjective) loudness between unoccluded and occluded conditions (insertion loss), MIRE data focused on the difference between measured sound pressure levels at a microphone placed inside the concha in the unoccluded and occluded conditions (also a measure of insertion loss), and is thus an objective measure. The attenuation values afforded in the REAT test were computed as a difference between the occluded and unoccluded conditions (i.e., occluded – unoccluded)

since, in the occluded condition, the stimuli (1/3 octave band centers) must be louder (higher in intensity, or dB) to be heard by the participants. The MIRE tests, however, with the microphone placement inside the concha, utilized an attenuation calculation that is the *reverse* of that in REAT (i.e., unoccluded – occluded). This was because that, in the unoccluded condition, the microphone measured a louder (higher in intensity, or dB) stimulus than it would in the occluded condition, which by definition had the microphone ‘blocked’ such that the stimulus measured is actually lower in intensity, at least in most cases.

MIRE results (averaged across left and right ears) for the Sony NC-20, Sennheiser PXC-250, and Bose QC-2 are presented in Figure 6.

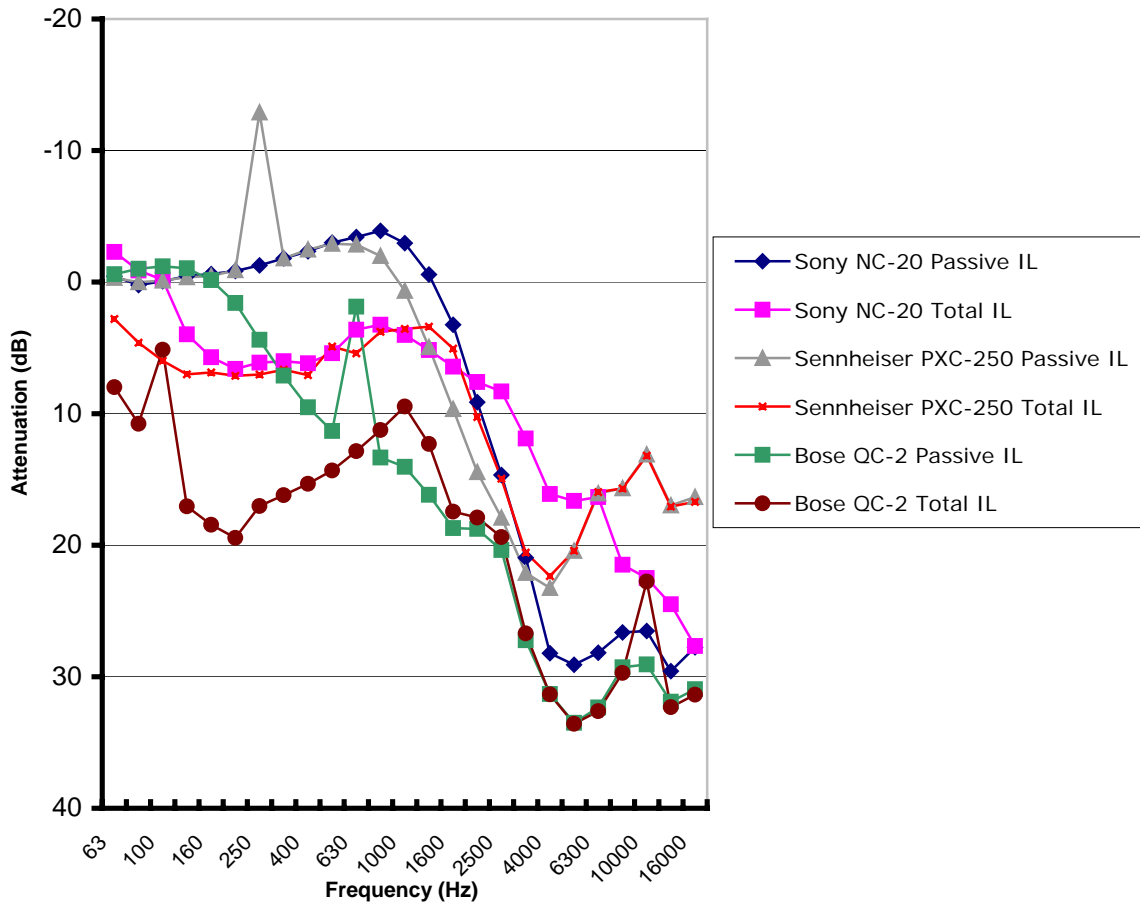


Figure 6. MIRE measurements of three ANR devices with passive and total insertion loss plotted (data averaged across left and right ears).

The Bose Quiet Comfort 2 resulted in the greatest overall attenuation of the three tested products. As ANR devices function best in the lower frequencies, the

ability of the Bose product to attenuate noise when compared to the other two products is quite compelling. This effect is shown in Figure 6. Note how the lower frequencies were attenuated with the electronics turned on for the Bose product, an effect that was less apparent as frequencies increased up until about 1000 Hz, where attenuation again generally increases with increasing frequency. Indeed, the passive abilities of the Bose product closely mirrored its active abilities over and above about 2500 Hz. The Sony product, on the other hand, generally exhibited decreased attenuation ability, in both passive and active modes, when compared with the Bose product. Total IL for the Sony device is only marginally more effective in the low frequencies than the Bose device's passive ability—at frequencies over and above about 315 Hz the passive qualities of the Bose product outperform the active qualities of the Sony product. It is readily apparent how the Sony product's circumaural design with holes resulted in overall decreased attenuation when compared to the Bose's more solid circumaural design. One can also see that the total attenuation component of the Sennheiser product closely mirrors that of the Sony product up to about 2000 Hz, where the Sennheiser product improves somewhat until about 8000 Hz, where they diverge with the Sony product providing improved attenuation beyond. At frequencies above about 4000 Hz, the Sennheiser's active and passive qualities are almost identical (similar in trend to the Bose product, which has higher attenuation). Interestingly, the NC-20's passive component closely mirrored the Sennheiser's passive component as well, even though the products differed in basic design (i.e., circumaural and supra-aural). This result was further evidence that the Sony earcup design (with its holes, shallow earcup, and resulting noise transmission pathways), even though circumaural, was closer to a supra-aural design with respect to attenuation performance.

All Devices: REAT and MIRE Results

The results for REAT and MIRE data for all devices are depicted in Figure 7. Comparison of the REAT and MIRE results together again reveals the superior attenuating abilities of the Shure products. The spectral attenuation performance of the E3c device with the foam tip, and its NRR score of 25, was the highest of all the devices tested. It appeared that the foam tips provided improved attenuation over the flanged tips for both of the Shure products (especially for the E3c), although even with the flanged tips both products provided generally higher attenuation when compared to the other products tested. Conversely, the Sony NC-20, in either passive or active mode, generally performed weaker with respect to its attenuating abilities in both REAT and MIRE testing. Notwithstanding the NC-20's NRR of -7, the weak active attenuation is further hampered by the fact that the MIRE measurements indicated that only one of the two earcups (the right side earcup) was actually reducing noise in the low frequencies (i.e., using ANR). This effect was reproduced in both NC-20 samples tested; thus, it is possible that the result is not isolated to these samples. The Bose product performed well in active mode, attenuating the lower frequencies up to about 800 Hz. The Sennheiser product's supra-aural design provided

moderate attenuation in active mode that closely mirrored the performance of the NC-20 in its active mode in the low frequencies. Even in the low frequencies, the Sennheiser’s active mode insertion loss was only marginally improved over that of REAT, which was likely due to its supra-aural design.

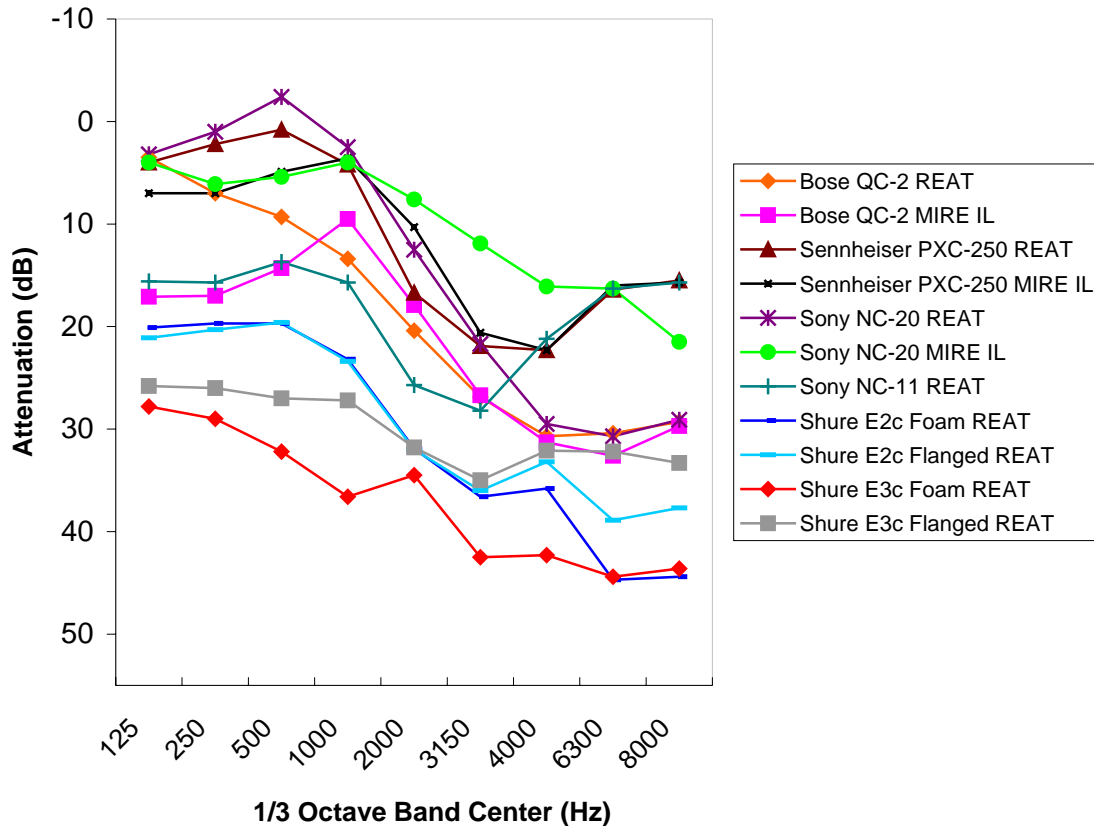


Figure 7. REAT passive and MIRE total (passive + active) attenuation data for all devices.

The Sony NC-11’s REAT performance was found to be similar to the Bose product’s active mode performance up until about 500 Hz, where they diverge and the NC-11 performs slightly better before degrading at and above 3150 Hz. It would have been interesting to see how well or how poorly the NC-11’s active mode performance was but, as described earlier, this was not realized because, in spite of repeated attempts, it could not be tested reliably with miniature microphones.

As stated previously, the complete attenuation data sets for REAT and MIRE measurements appear on the attached CD of Appendix 1.

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