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ABSTRACT

In connection with a European joint project regarding attenuation of impulsive sounds by hearing protectors an additional experiment was performed on 16 subjects comparing the standardised subjective method (ISO 4869-1) with an objective method for assessing the attenuation of ear muffs. For the objective method a probe microphone was used with a frame supporting the microphone in the concha and with a 12.5 mm probe tube. At 125 and 250 Hz there was 2-3 dB difference between the two methods in a direction opposite to that expected due to physiological noise. The reason was probably the actual realisation of the sound field. At 4 and 6.3 kHz the objective results were 7 dB lower, probably due to dips at the probe tip in the standing wave in the ear canal. The objective method is much faster and gave slightly smaller standard deviations, which support the idea to use that as a standardised method in the future. However, the optimal microphone technique has still not been found.

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INTRODUCTION

The standardised method to evaluate attenuation of hearing protectors (ISO 4869-1) has a couple of drawbacks. It is generally accepted that the attenuation at the lowest frequencies is overestimated due to physiological noise, which would give threshold values that are too high with the hearing protector on (Berger & Kerivan, 1983; Smoorenburg et al., 1993). Furthermore, when used in high level noise the attenuation value will be different from the measured one if any nonlinearity is present. There are hearing protectors constructed to give higher attenuation at high levels and maybe even amplification at low levels, i.e. nonlinear on purpose. Finally, the threshold values are subject to some variability.

These problems might be overcome by measuring the sound pressure level in the ear canals of the subjects with and without hearing protector. Such a method was investigated by Smoorenburg et al. (1993).

The purpose of the present experiment was to compare attenuation values obtained by the subjective threshold method standardised in ISO 4869-1 with attenuation values in the same sound field obtained by the microphone-in-real-ear (MIRE) technique developed at TNO, Soesterberg, Holland.

The experiment was performed in connection with another investigation on the same ear muffs and subjects in an anechoic room, with the purpose to assess the attenuation of ear muffs as a function of the angle of incidence of the sound (Hagerman et al., 1994).

The latter experiment was part of a research program set up within the third program of the EC Bureau Communautaire de Référence, 1993-1994. Nine European laboratories were involved in this project, of which TNO Institute of perception, Soesterberg, Holland was the coordinator.

METHODS

Equipment

The subject was seated in a sound-insulated booth (1.50 x 2.00 x 1.95 m^3). That is our ordinary room for testing hearing protectors according to the standard ISO 4869-1. Altogether 12 small loudspeakers are used to create the sound field. Four are placed in the upper corners of the room, four in the lower corners and four lateral to the subject at the intersections between the walls and the ceiling / floor. However, for the frequencies 125 and 250 Hz two bigger loudspeakers are used instead. They are placed on the floor in front of and behind the subject.

Subjective measurements

The electronic equipment used was built at our department. The loudspeakers are normally fed from two uncorrelated noise generators through two separate computer controlled third-octave filters and attenuators. The computer is a Luxor ABC 806. These parts of the equipment were used for the subjective measurements. Békésy thresholds without and with hearing protector were measured with 14 turning points. The threshold was calculated as the mean of the 12 last turning points. The subjective method is denoted REAT (Real Ear Attenuation at Threshold) in the following.

Objective measurements

The objective measurements were performed in the right ear canal of the subject in the sound-insulated booth without and with hearing protector. The sound level in the ear canal was measured according to the MIRE-method (Microphone In Real Ear) developed at TNO, Soesterberg, Holland. The microphone type used was a Sennheiser KE-211-9 equipped with a probe tube 12.5 mm of length, inner diameter 1 mm and outer diameter 2.2 mm. It was mounted on a wire arrangement used to support it in the ear (Smoorenburg et al., 1993). The whole assembly was bought from TNO. The preamplifier was built by us, according to a construction from TNO.

When normal psycho-acoustical measurements are performed in the room the two channels have inputs from two independent noise sources with equal spectral density function, $S_{xx}(f)$. If the channels have transfer functions $H_A(f)$ and $H_B(f)$ the total spectral density function of the summation signal $Y(f)$ will be

$$S_{yy}(f) = S_{xx}(f) * |H_A(f)|^2 + S_{xx}(f) * |H_B(f)|^2$$

The subject will respond to the level (RMS-value) of $Y(f)$.

$$y_{RMS} = \left[\int_{-\infty}^{\infty} S_{yy}(f)\, df \right]^{1/2}$$

Normally $S_{xx}(f)$ is constrained to 1/3 octave band.
As can be seen from the formulas above the only thing that has to be known to calculate the RMS-value in a subjects ear canal are the transfer functions of the two channels and the spectral density of the noise. To speed up the measurements we therefore used a chirp as the test signal instead of random noise. It was produced by the hardware equipment TAMP3 developed at our laboratory. The period time was 16.7 ms (60 Hz periodicity) and 100 periods was used for each measurement giving a measurement time of 1.67 s. The measurements were performed between 120 and 9000 Hz. For the analysis the same equipment was used together with the software program NAP (Network Analysis Program) also developed at our laboratory. The level of the chirp signal at the reference point was approximately 75 dB SPL for measurements without a hearing protector and 10 dB higher, i.e. approximately 85 dB SPL for measurements with a hearing protector.

For each case, i.e. with and without ear muff, two measurements were performed with the chirp signal supplied instead of each one of the two noise sources respectively. To get results corresponding to measurements with the uncorrelated noise sources we measure the transfer function of each channel separately, do the spectral summation and estimate the level for a 1/3-octave band of noise centered around each frequency bin. This is done with and without hearing protector. The difference in 1/3 octave band level is taken as an estimate of the attenuation of the hearing protector.

After the experiment it was found that the subjects by mistake had been placed about 7 cm above the reference point. (This was true both for the subjective and for the objective measurements.) Therefore the requirement of ISO 4869-1 on the homogeinity of the field was not fulfilled. The deviation from the reference level exceeded the allowed 2.5 dB in 11 out of 42 measured cases (6 microphone placements times 7 octave frequencies) and greater than 3.5 dB in 5 of these 11 cases. At 125 Hz there were 4 deviations greater than 2.5 dB and at 500 Hz there were 3 deviations greater than 2.5 dB. At no other frequency there were more than one deviation greater than 2.5 dB.

Hearing protectors

Three earmuffs were tested, Bilsom Viking 2421, Peltor H7A and Willson 358A. One sample of each type was used. They were not conditioned before the test.

Subjects

Sixteen subjects participated, 15 males and 1 female. Their mean age was 27 years. They were tested for normal hearing. All of them had hearing thresholds better than 15 dB HL between 125 and 2000 Hz and better than 25 dB HL between 3000 and 8000 Hz.

Procedure

Nine subjects participated at a practise session. Their pure tone thresholds with earphones were checked for normal hearing and they practised on the Békésy thresholds in the sound field for two complete audiograms. The rest of the subjects were experienced. They were tested for normal hearing at earlier sessions and were therefore just screened at 20 dB HL before starting the test session. The subjects were instructed by the experimenter, put on the ear muff themselves and adjusted it while listening to a broad-band noise of about 80 dB SPL from the loudspeaker. Subjective thresholds were measured first without and then with the hearing protectors. The order of the type of protector was permutated among the subjects, but was the same at the subjective and objective measurements.

The objective measurements were performed a couple of weeks later, at the same session as in the experiment by Hagerman et al. (1994). In that session about half of the subjects started with the measurement in the sound proof booth and then went directly to measurements in the anechoic chamber, the results of which are not reported here. The other subjects were measured in the opposite order. The probe microphone remained in the ear canal during the whole session.

RESULTS

REAT versus MIRE results

In Figure 1 attenuation curves for the two measurement methods are shown averaged over 16 subjects and 3 types of muffs. Analysis of variance showed that all the factors tested, i.e. frequency, type of muff, subject and type of measurement, were highly significant ($p<0.0001$). As seen in Figure 1 there were differences between the two methods at 125, 250 and 500 Hz as well as in the frequency range 4000-8000 Hz. These differences were all significant, $p<0.005$ for 125 Hz $p<0.0001$ for 250 Hz, $p<0.01$ for 500 Hz and $p<0.0001$ for 4000-8000 Hz.

In Figure 2 a-c it is shown that these differences are similar for all the three muffs, except for Willson 358A at 125 and 250 Hz. The difference values are listed in Table I.

Table I. Attenuation differences in dB between the two methods (REAT minus MIRE) for each type of ear muff averaged over 16 subjects.

Freq., kHz	.125	.25	.5	1	2	3.15	4	6.3	8
Bilsom Viking	-2.6	6.0	1.0	-1.4	-1.3	0.2	11.4	9.8	5.5
Peltor H7A	-2.8	-4.7	1.2	0.0	1.7	-2.8	5.0	4.0	4.6
Willson 358A	0.3	1.0	3.0	2.2	1.5	-0.5	5.8	7.5	4.6
Mean	**-1.7**	**-3.2**	**1.7**	**0.3**	**0.7**	**-1.0**	**7.4**	**7.1**	**4.9**

In a pilot study preceeding the main experiment measurements were made on two subjects with the ordinary probe and with a modified probe that was 6 mm longer. The reason for that was that the pilot measurements with the ordinary probe tube showed a dip in the attenuation curve at 5 kHz. The results of the comparisons are shown in Table II and agree rather well with the results of Hellström (1993) for various placements of the probe tip in the ear canal.

Table II. Attenuation differences in dB between measurements with a modified probe that was 6 mm longer the and with the ordinary probe. Two subjects not participating in the main experiment. Bilsom Viking 2421.

Freq., kHz	.25	.5	1	2	3.15	4	5	6.3	7	8
Subject 1	-1.7	-0.5	-4.0	0.6	-0.5	0.5	6.0	2.0	4.7	2.5
Subject 2	1.2	1.5	1.5	1.5	2.0	4.0	11.3	5.2	4.0	-3.0
Mean	**-0.2**	**0.5**	**-1.2**	**1.0**	**0.7**	**2.2**	**8.6**	**3.6**	**4.3**	**-0.2**

In spite of these results the ordinary probe was chosen for the main study. There were two reasons for that decision. One was that this probe design was agreed upon between the various laboratories participating in the common European project. Another reason was that a similar experiment at TNO did not show this difference at high frequencies between REAT and MIRE measurements.

Since the subjective measurements include the two threshold measurements as a source of variance it was expected that the standard deviation for the objective measurements would be smaller. In Table III the standard deviations from subjective and objective measurements can be compared.

TABLE III. Standard deviations over 16 subjects for the subjective (REAT) and objective (MIRE) measurements. The last two rows are calculated as the square root of the mean variances over the three protector types.

Freq., kHz		.125	.25	.5	1	2	3.15	4	6.3	8
Bilsom	REAT	2.7	2.5	3.1	2.3	2.7	2.9	4.3	4.2	4.9
	MIRE	2.0	2.3	2.8	2.3	2.6	3.4	2.6	4.4	3.9
Peltor	REAT	3.0	2.4	2.5	2.7	2.4	2.6	2.9	3.3	4.0
	MIRE	1.7	2.5	2.6	3.0	3.3	3.3	2.2	3.2	3.6
Willson	REAT	4.4	6.3	5.0	5.5	3.3	3.4	4.3	6.2	6.9
	MIRE	4.6	7.1	4.5	4.7	4.0	2.5	2.1	5.5	6.6
Total	**REAT**	**3.4**	**4.1**	**3.7**	**3.8**	**2.8**	**3.0**	**3.9**	**4.8**	**5.4**
	MIRE	**3.0**	**4.6**	**3.4**	**3.5**	**3.4**	**3.1**	**2.3**	**4.5**	**4.9**

Collapsed over all frequencies the standard deviation for the subjective measurement was 3.95 dB and for the objective measurements 3.71 dB, calculated as the square root of the mean variances.

Comprehensive results for the REAT measurements are shown in Figures 3-5 and for the MIRE-measurements in Figures 6-8.

Diffuse field versus free field results

In the diffuse field the test signal reaches the protector from all directions. It is then expected that the attenuation measured for this condition depends on the worst case, i.e. when the sound comes from the direction where the lowest attenuation is obtained. Since we also made measurements on the same ear muffs and subjects for various angles of incidence in our anechoic chamber (Hagerman et al., 1994) this expectation can be checked. In Table IV below, the mean attenuation in the diffuse field can be compared to the lowest attenuation for the angles of incidence tested in the horizontal plane in the anechoic chamber.

Table IV. Attenuations and differences in dB between MIRE-measurements in the worst direction in the anechoic chamber and in the diffuse sound field for each type of ear muff. Mean over 16 subjects.

Freq., kHz		.125	.25	.5	1	2	3.15	4	6.3	8
Bilsom	anech.	8.7	14.0	28.0	30.3	33.0	36.5	41.5	30.0	31.5
	diffuse	13.3	22.5	29.5	31.9	36.2	37.3	31.8	31.6	34.4
	diff.	-4.6	-8.5	-1.5	-1.6	-3.2	-0.8	9.7	-1.6	-2.9
Peltor	anech.	9.0	14.0	29.0	34.0	32.0	35.0	34.5	26.5	26.5
	diffuse.	14.2	22.9	28.6	34.6	34.7	36.1	29.9	29.3	32.2
	diff.	-5.2	-8.9	0.4	-0.6	-2.7	-1.1	4.6	-2.8	-5.7
Willson	anech.	6.0	10.3	24.0	34.5	31.3	32.0	34.5	26.0	25.0
	diffuse.	8.9	16.3	22.8	32.8	32.6	30.8	30.1	26.1	27.2
	diff.	-2.9	-6.0	1.2	1.7	-1.3	1.2	4.4	-0.1	-2.2
Mean diff.		**-4.2**	**-7.8**	**0.0**	**-0.2**	**-2.4**	**-0.2**	**6.2**	**-1.5**	**-3.6**

DISCUSSION

Low frequencies

It was expected that the attenuation values at the lowest frequencies should be higher for the REAT measurements due to physiological noise. On the contrary they were 2 to 3 dB lower averaged over muff type. The result by Smoorenburg et al. (1993) showed about 3 dB difference at 125 Hz and about 1 dB difference at 250 Hz in the expected direction using the same type of probe. Brinkmann & Richter (1986) got no difference at 250 Hz but about 3 dB better attenuation at 125 Hz. Both these investigations showed differences in the same direction of 6 to 8 dB at 63 Hz. Thus it seems like we have got 3 to 4 dB too low attenuation from the subjective measurements at 125 and 250 Hz.

The reason for our result is difficult to explain. One reason might have been low frequency noise in the room giving to high thresholds without protectors which would lead to lower attenuation values. However, this was ruled out by noise measurements after the experiment showing that the noise requirement of ISO 4869-1 was fulfilled. Another reason might be the inhomogeinity of the field especially at 125 Hz, where a certain directionality of the field was also found due to resonances in the wall of the right side. It has to be considered that the subjective threshold measurements were performed binaurally, whereas the objective measurements were performed for the right ear only. However, for 250 Hz the sound field fulfilled all the requirements with good margins. From Table IV and Table I it can be seen that the MIRE-results at 125 and 250 Hz in the anechoic chamber is more close to the expected, since they are a couple of dB lower than the REAT-values. This still points to the diffuse sound field as the problem, e.g. giving different sound pressure levels at the two ears.

High frequencies

The differences between the two methods at high frequencies obtained in this experiment were not found by Smoorenburg et al. (1993) or by Brinkmann & Richter (1986). However, the latter did not use a probe tube in the ear canal, but rather a small microphone placed in the outer part of the ear canal.

The probe length of 12.5 mm used means that the average distance of the probe tip to the ear drum would be about 14 mm, which corresponds to a quarter wave length at 6 kHz. Standing waves in the ear canal due to reflections at the ear drum would thus give a low sound pressure level around 6 kHz without protector and a dip in the frequency response curve, which has been shown clearly by Hellström (1993). With protector, however, the wave propagation in the ear canal may be different, e.g. due to bone conducted sound or due to reflections from the protector. Then the dip may be moved to another frequency. Taking the difference (as in Tables I and II) between two similar curves with dips at slightly different frequencies, fluctuations in this frequency area will occur.

There was also a difference of 6 dB at 4 kHz between the MIRE-results in the worst direction in the anechoic chamber and in the diffuse sound field. This can not have been caused by the probe, since it was not moved between the two measurements. The reason might be that the worst direction for 4 kHz is not in the horizontal plane, but from above or from below. However, there is no similar tendency at the adjacent frequencies 3.15 or 6.3 kHz.

FIGURES

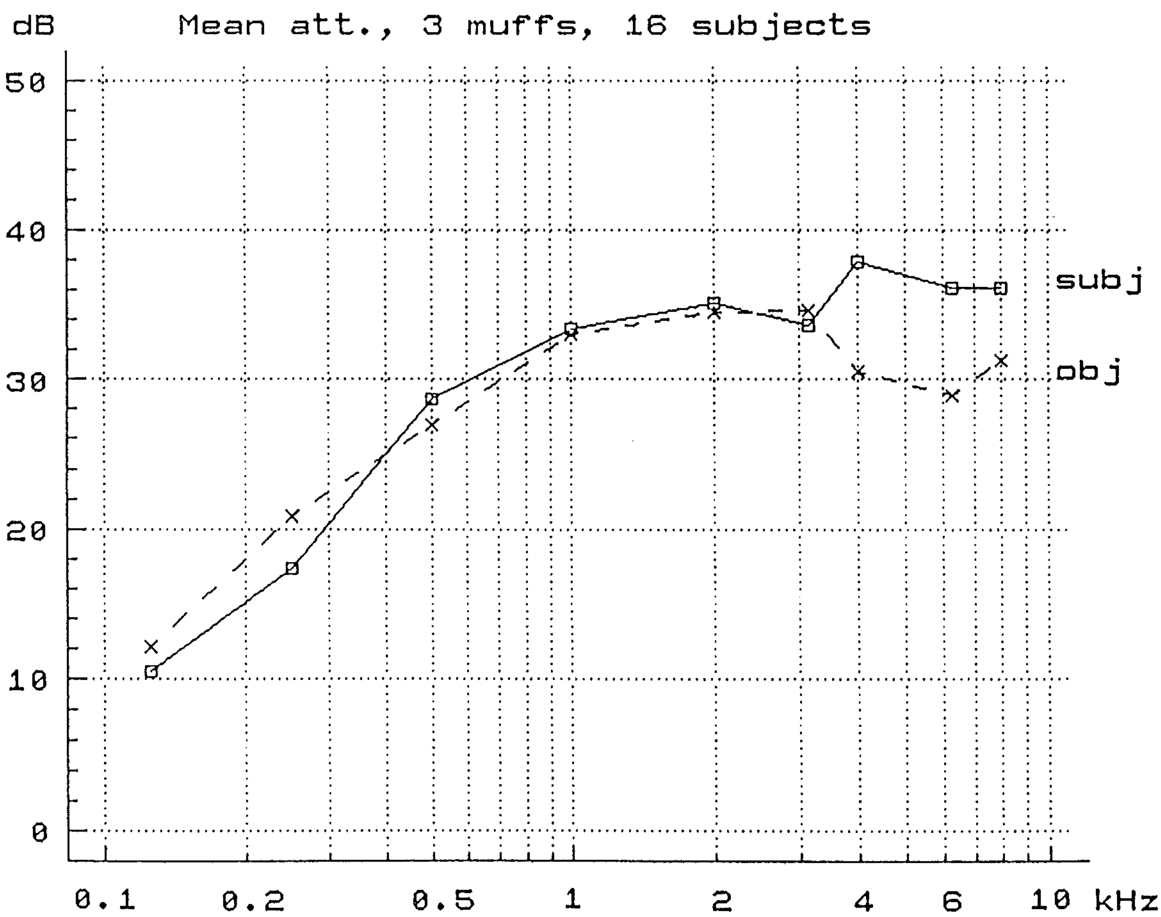

Figure 1. Mean attenuation over 3 ear muffs and 16 subjects as a function of frequency. Solid line refers to REAT measurements and dashed line refers to MIRE measurements.

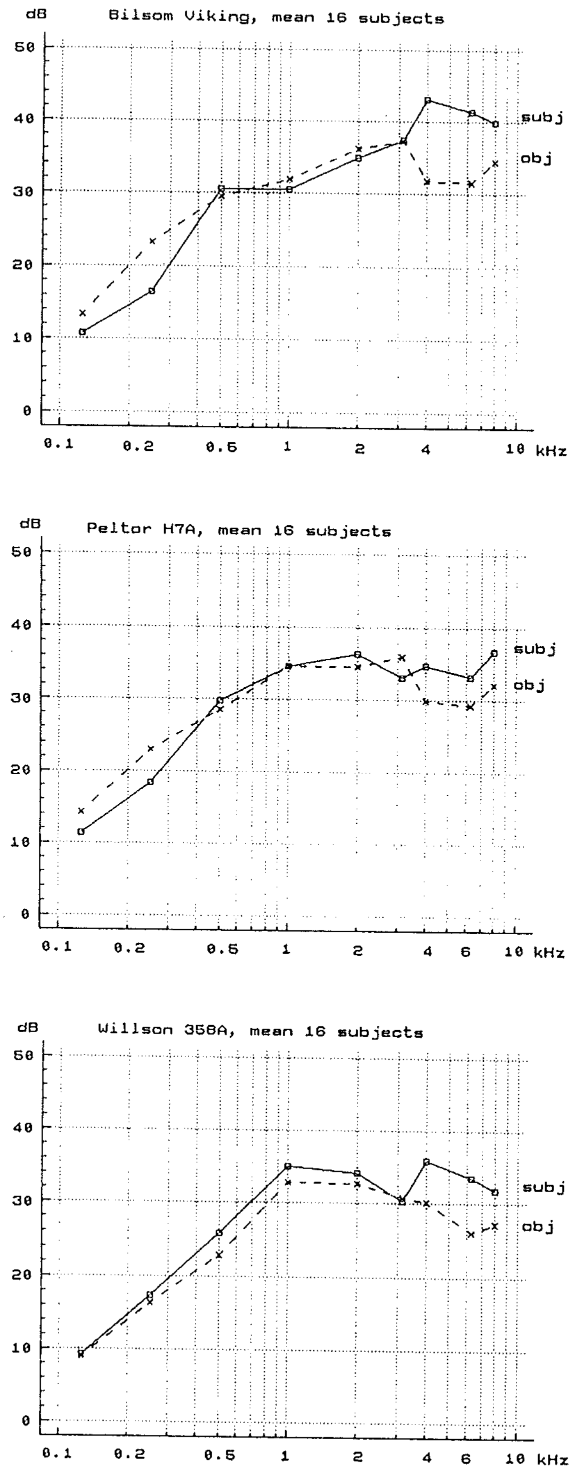

Figure 2a-c. Mean attenuation over 16 subjects as a function of frequency for the three ear muffs respectively. Solid line refers to REAT measurements and dashed line refers to MIRE measurements.

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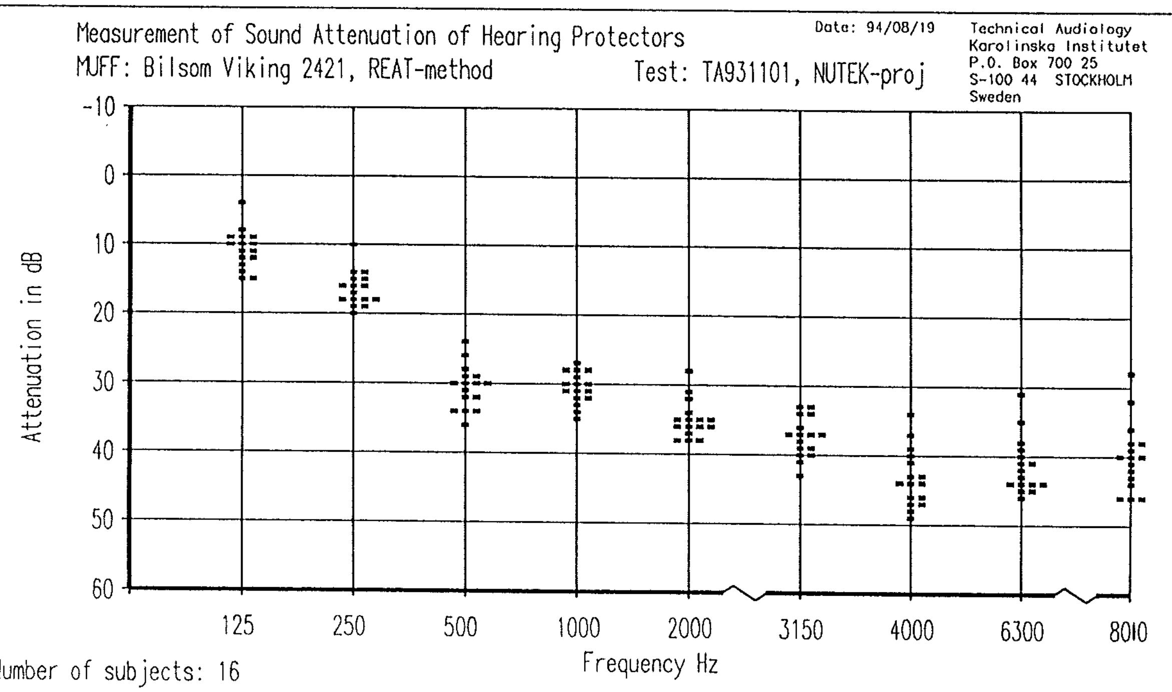

Number of subjects: 16

Attenuation in dB	125	250	500	1000	2000	3150	4000	6300	8010
Lower quartile	9	15	29	28	34	35	40	39	38
Range	11.0	9.7	11.6	8.6	10.2	10.3	15.0	15.9	17.4
Stand. dev	2.7	2.5	3.1	2.3	2.7	2.9	4.3	4.2	4.9
Median	10.5	16.6	30.3	30.6	35.5	37.3	44.0	42.6	40.2
Mean	10.7	16.5	30.5	30.5	34.9	37.4	43.2	41.4	39.9

Test method according to standard SS 88 21 51 app. A and ISO 4869-1(1990).

Figure 3. Comprehensive REAT-data for Bilsom Viking 2421.

Measurement of Sound Attenuation of Hearing Protectors
MUFF: Peltor H7A, REAT-method

Date: 94/08/19

Test: TA931102, NUTEK-proj

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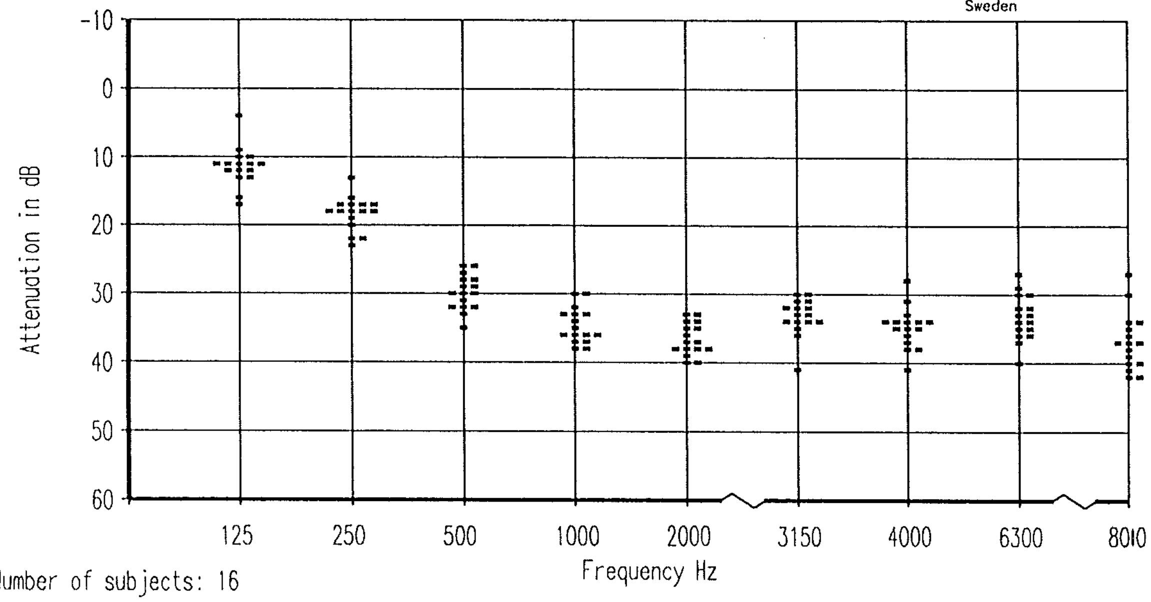

Number of subjects: 16

Attenuation in dB	125	250	500	1000	2000	3150	4000	6300	8010
Lower quartile	10	17	28	33	35	31	34	31	34
Range	13.8	9.4	9.1	8.7	7.6	11.0	12.7	12.8	14.6
Stand. dev	3.0	2.4	2.5	2.7	2.4	2.6	2.9	3.3	4.0
Median	11.2	17.8	29.7	35.4	36.7	33.2	34.5	33.5	37.0
Mean	11.4	18.3	29.8	34.7	36.4	33.2	34.8	33.3	36.8

Test method according to standard SS 88 21 51 app. A and ISO 4869-1(1990).

Figure 4. Comprehensive REAT-data for Peltor H7A.

Measurement of Sound Attenuation of Hearing Protectors
MUFF: Willson 358A, REAT-method

Date: 94/08/19

Test: TA931103, NUTEK-proj

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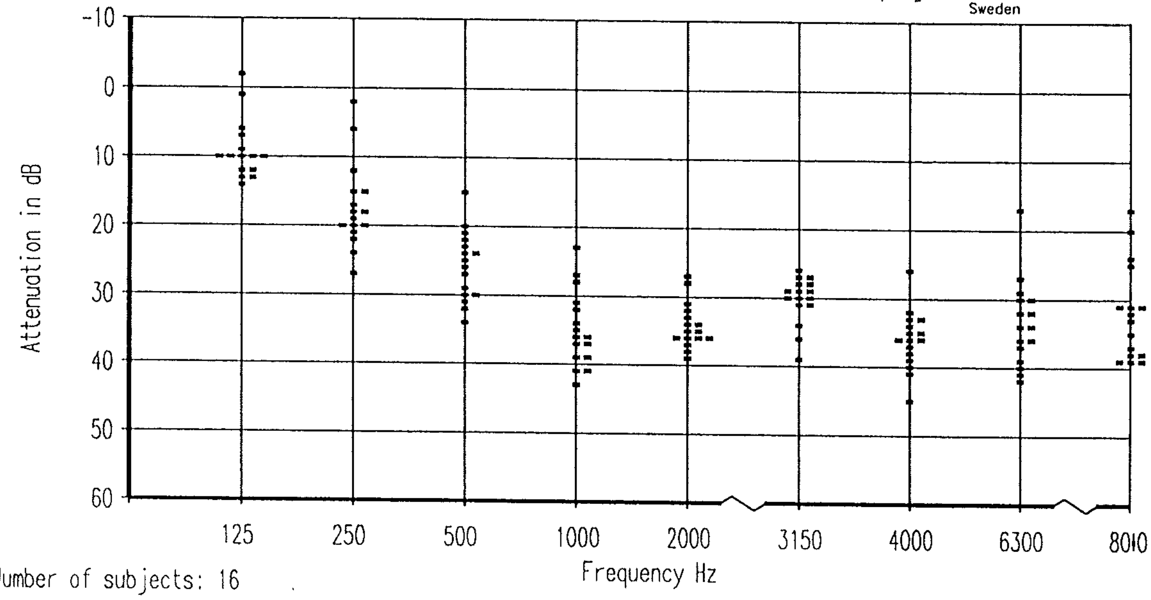

Number of subjects: 16

Attenuation in dB	125	250	500	1000	2000	3150	4000	6300	8010
Lower quartile	9	15	22	31	32	28	33	30	25
Range	15.7	25.0	19.1	19.4	11.8	12.6	19.0	24.6	21.9
Stand. dev	4.4	6.3	5.0	5.5	3.3	3.4	4.3	6.2	6.9
Median	10.5	18.7	25.4	36.0	35.1	29.4	35.6	33.7	32.3
Mean	9.2	17.3	25.8	35.0	34.2	30.3	35.9	33.6	31.8

Test method according to standard SS 88 21 51 app. A and ISO 4869-1(1990).

Figure 5. Comprehensive REAT-data for Willson 358A.

Measurement of Sound Attenuation of Hearing Protectors

MUFF: Bilsom Viking 2421, MIRE-method

Date: 94/08/18

Test: TA931201, NUTEK-proj

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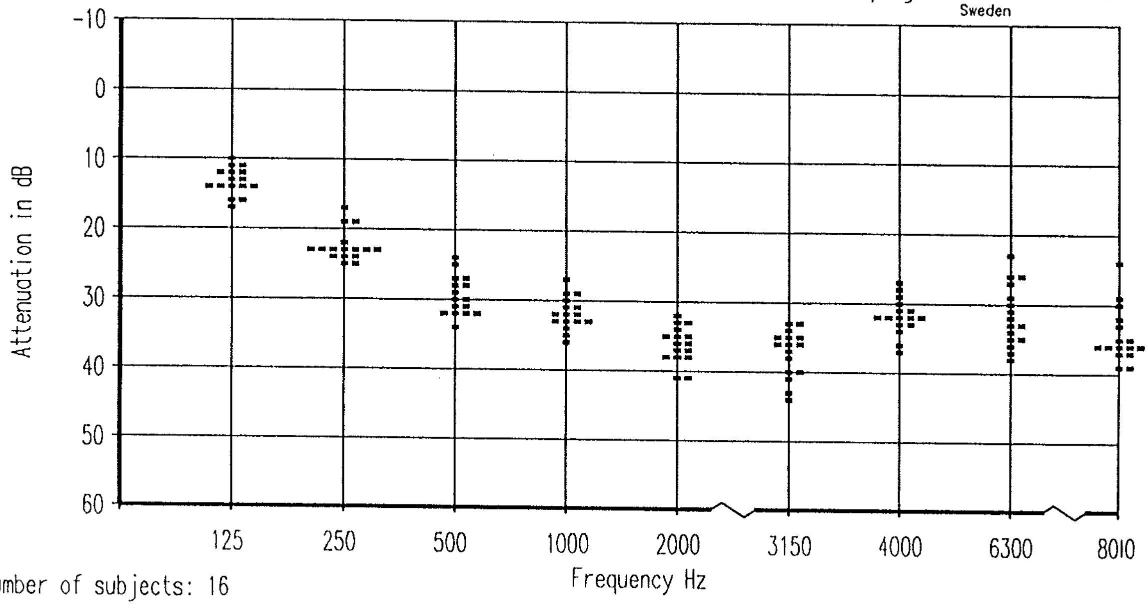
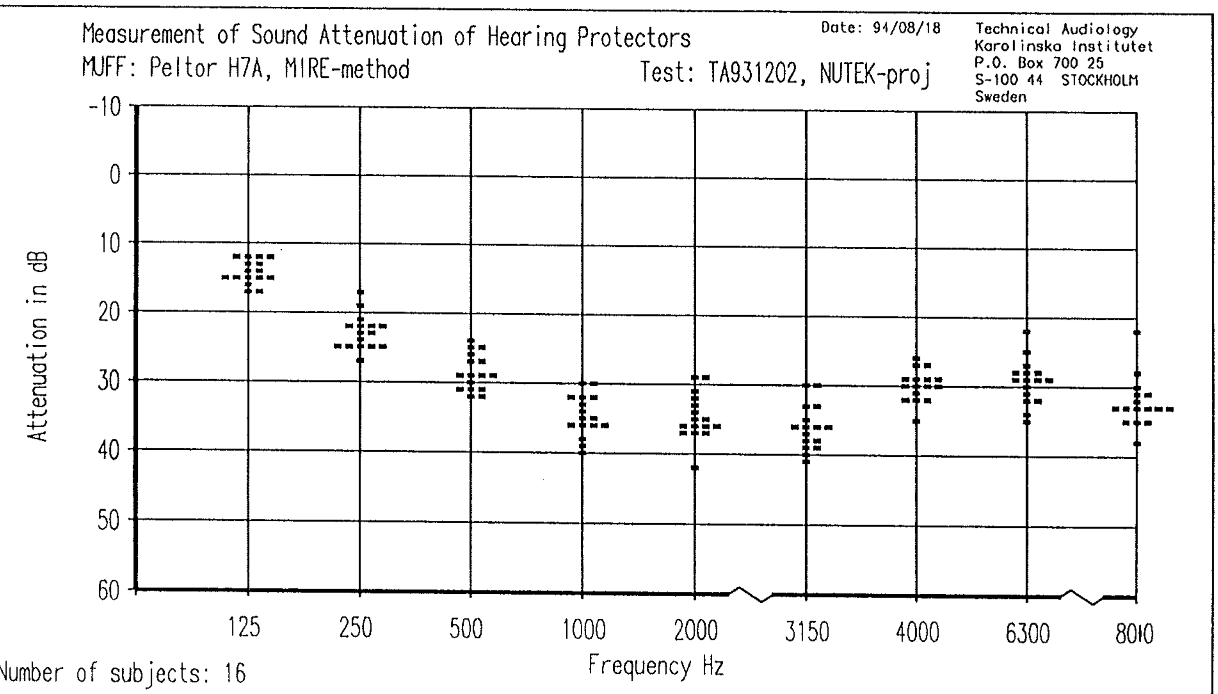


Number of subjects: 16

Attenuation in dB	125	250	500	1000	2000	3150	4000	6300	8010
Lower quartile	12	22	27	30	34	35	30	27	32
Range	7.0	8.0	10.0	9.0	9.0	11.0	10.0	15.0	15.0
Stand. dev	2.0	2.3	2.8	2.3	2.6	3.4	2.6	4.4	3.9
Median	13.5	23.0	30.0	32.0	36.0	36.0	32.0	32.5	36.0
Mean	13.3	22.5	29.5	31.9	36.2	37.2	31.8	31.6	34.4

Figure 6. Comprehensive MIRE-data for Bilsom Viking 2421.



Number of subjects: 16

Attenuation in dB	125	250	500	1000	2000	3150	4000	6300	8010
Lower quartile	12	22	26	32	32	33	29	28	31
Range	5.0	10.0	8.0	10.0	13.0	11.0	9.0	13.0	16.0
Stand. dev	1.7	2.5	2.6	3.0	3.3	3.3	2.2	3.2	3.6
Median	14.5	23.0	29.0	35.0	35.5	36.0	30.0	29.0	33.0
Mean	14.2	22.9	28.6	34.6	34.7	36.1	29.9	29.2	32.2

Figure 7. Comprehensive MIRE-data for Peltor H7A.

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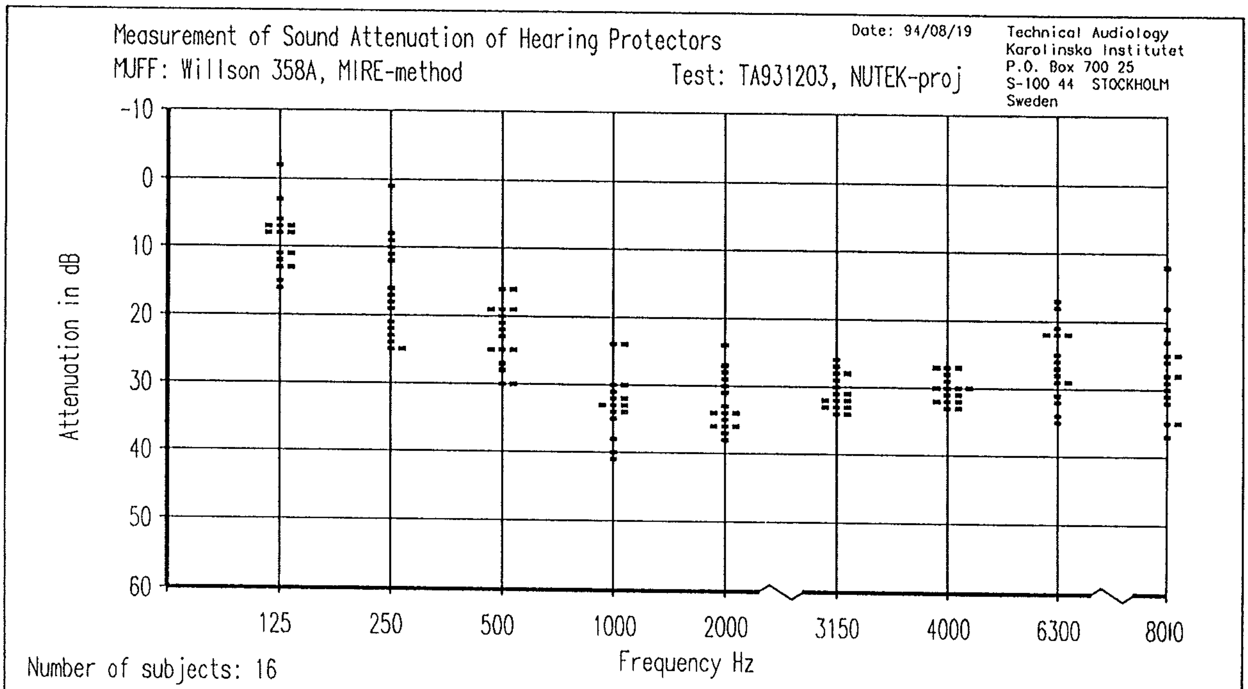

Number of subjects: 16

Attenuation in dB									
Lower quartile	7	10	19	30	29	28	28	22	23
Range	18.0	24.0	14.0	17.0	14.0	8.0	6.0	18.0	25.0
Stand. dev	4.6	7.1	4.5	4.7	4.0	2.5	2.1	5.5	6.6
Median	8.0	17.5	22.5	33.0	34.0	31.5	30.0	26.5	28.0
Mean	8.9	16.3	22.8	32.8	32.6	30.8	30.1	26.1	27.2

Figure 8. Comprehensive MIRE-data for Willson 358A.