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Sound attenuation of hearing protectors in use at work

– Study conducted from 2005 to 2007 –

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Abstract

Hearing protectors used at work often reduce noise levels less effectively than during type testing. This is known from international publications and from an earlier study by the BGIA, Institute for Occupational Safety and Health of the German Social Accident Insurance (Deutsche Gesetzliche Unfallversicherung, DGUV). The Working Group "Hearing Protection" of the Expert Committee "Personal Protective Equipment" of the German Social Accident Insurance therefore initiated a study to determine the actual sound attenuation of hearing protectors used at workplaces. In cooperation with several institutions for statutory accident insurance and prevention, the sound attenuation of the hearing protectors used in various branches of industry was measured. The measuring method replicated as far as possible that used for type testing in the laboratory in accordance with DIN ISO 4869-1. On average, all of the products yielded lower sound attenuation in practice than in laboratory measurements. The effect is biggest with ear-plugs that have to be shaped before use, with a mean deviation of 7.8 dB. Other types of plugs showed less difference, with values of 5.0 and 4.5 dB. For ear-muffs the difference is 3.0 dB, and for custom moulded ear-plugs a value of 6.0 dB is achieved if they are not checked prior to use to help ensure individual quality fit. No data were obtained for products that had been checked. To improve the use of hearing protection in the field, employees should receive instruction at work or during occupational medical check-ups that draws attention to the care required when inserting/fitting hearing protectors. This applies particularly in the case of ear-plugs that have to be shaped before use.

Schalldämmung von Gehörschützern in der betrieblichen Praxis – Studie von 2005 bis 2007 –

Kurzfassung

Gehörschutz erreicht beim betrieblichen Einsatz oft eine geringere Schalldämmung als in der Baumusterprüfung. Dies ist aus internationalen Veröffentlichungen sowie einer früheren Studie des BGIA – Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung bekannt. Daher initiierte der Arbeitskreis „Gehörschutz" im Fachausschuss „Persönliche Schutzausrüstung" der Deutschen Gesetzlichen Unfallversicherung (DGUV) eine Untersuchung, um die in der Praxis tatsächlich erreichte Schalldämmung von Gehörschutz zu ermitteln. In Zusammenarbeit mit mehreren Berufsgenossenschaften wurde in verschiedenen Industriebereichen die Schalldämmung dort verwendeter Gehörschützer gemessen. Das Messverfahren war dem zur Baumusterprüfung im Labor nach DIN ISO 4869-1 so weit wie möglich nachgebildet. Für alle Produkte ergab sich in der Praxis im Mittel eine geringere Schalldämmung als in den Labormessungen. Am deutlichsten ist der Effekt für vor Gebrauch zu formende Gehörschutzstöpsel mit einer mittleren Abweichung von 7,8 dB. Andere Stöpselvarianten weisen mit 5,0 dB und 4,5 dB geringere Unterschiede auf. Für Kapselgehörschützer ergibt sich eine Differenz von 3,0 dB, für individuell angepasste Otoplastiken ein Wert von 6,0 dB, falls bei der Auslieferung keine Funktionskontrolle durchgeführt wurde. Für Produkte mit Funktionskontrolle wurden keine Daten ermittelt. Um die Benutzung von Gehörschutz in der Praxis zu verbessern, sollten Beschäftigte bei Unterweisungen im Betrieb oder bei der arbeitsmedizinischen Vorsorge auf die erforderliche Sorgfalt beim Ein- und Aufsetzen von Gehörschutz hingewiesen werden. Dies gilt insbesondere, wenn vor Gebrauch zu formende Gehörschutzstöpsel verwendet werden.

Efficacité de protecteurs individuels contre le bruit dans la pratique – Etude de 2005 à 2007 –

Résumé

D’après des publications internationales et une étude antérieure du BGIA (Institut pour la sécurité et santé du travail des organismes d’assurance et de prévention des risques professionnels), il ressort que, dans les conditions de port, l'atténuation acoustique réelle obtenue avec des protections auditives est souvent inférieure à celle obtenue lors de l'essai de type. C’est la raison pour laquelle le groupe de travail « Protections auditives » au sein de la commission technique « Équipement de protection individuelle » des caisses légales allemandes d’assurance accident (DGUV) est à l’origine d’une étude visant à déterminer l’efficacité réelle de protections auditives. L’atténuation acoustique obtenue avec des protecteurs individuels contre le bruit utilisés dans différents secteurs industriels a été mesurée en collaboration avec plusieurs caisses mutuelles d’assurance accident. La méthode de mesure était la plus analogue possible à celle mise en œuvre dans le cadre de l’essai de type selon DIN ISO 4869-1 réalisé au laboratoire. Pour tous les produits, l’atténuation moyenne mesurée dans la pratique était inférieure à celle mesurée au laboratoire. Ce phénomène est le plus prononcé dans le cas des bouchons d’oreilles formables avant usage, l’écart moyen mesuré étant de 7,8 dB. D’autres variantes de bouchons d’oreilles présentent des différences plus faibles (5,0 dB et 4,5 dB). Pour les protecteurs munis de « coquilles » (serre-têtes), la différence est de 3,0 dB et, pour les protections auditives sur mesure, de 6,0 dB si aucun contrôle fonctionnel n'a été réalisé lors de la livraison. Aucune mesure n’a été effectuée pour les produits ayant subi un contrôle fonctionnel. Afin d’améliorer l’efficacité des protections auditives dans la pratique, il faut, dans le cadre de formations dans l'entreprise ou de la prévention assurée par le médecin du travail, que l’attention des salariés soit attirée sur le fait que celles-ci doivent être mises en place avec soin. Ceci est valable, en particulier, pour les bouchons d’oreilles à modeler avant usage.

Insonorización de los protectores auditivos en la práctica empresarial – Estudio desde 2005 hásta 2007 –

Resumen

Con frecuencia, la protección auditiva consigue una peor insonorización en su utilización en la empresa que en las pruebas de homologación. Esto es conocido a través de los informes internacionales así como gracias a un estudio anterior del BGIA – Instituto para la Protecciòn Laboral del Seguro Obligatorio de Accidentes Alemán. Es por ello que el grupo de trabajo „Protección auditiva“ de la comisión de expertos „Equipamiento de protección“ del Seguro Obligatorio de Accidentes Alemán ha puesto en marcha un estudio con el cual determinar la insonorización que la protección auditiva alcanza efectivamente en la práctica. En colaboración con varias mutuas de seguro patronal, se ha medido la insonorización de las protecciones auditivas utilizadas en distintas ramas industriales. El procedimiento de medición se ha adaptado lo más posible al utilizado en las pruebas de homologación en laboratorio según DIN ISO 4869-1. En todos los productos, ha resultado que la insonorización media es menor que la de las mediciones de laboratorio. El efecto más claro se registra en los tapones de protección auditiva a los que hay que dar forma antes del uso, con una desviación media de 7,8 dB. Otros tipos de tapones registran menores desviaciones de 5,0 dB y 4,5 dB. En los auriculares antirruido, se da una desviación de 3,0 dB; en las piezas moldeadas auditivas adaptadas individualmente el valor es de 6,0 dB cuando el suministro no se somete a controles de funcionamiento. No se han obtenido datos para los productos con control de funcionamiento. A efectos de mejorar la protección auditiva en la práctica empresarial, el personal ha de ser advertido a través de las instrucciones impartidas en la empresa o en el marco de las medidas de prevención médico-sanitarias del necesario cuidado al utilizar y ponerse la protección auditiva. Lo que es especialmente importante cuando se utilizan tapones a los que hay que dar forma antes del uso.

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Content

1 Introduction

In March 2007, the Noise and Vibration OSH Ordinance came into force in Germany, transposing the EC Noise at Work Directive (2003/10/EC) into German law. Its relevance to the use of hearing protection is twofold. Firstly, it reduces the exposure action values, at and above which hearing protection must be provided/worn, by 5 dB. Secondly, the German Ordinance introduces a new variable, the maximum permissible exposure value[1], which must be observed at the employee's ear when hearing protection is worn ([1] Section 8 (2)). The maximum permissible exposure value for continuous noise over eight hours is 85 dB(A), and for the peak value of the sound-pressure level 137 dB(C).

In order for this value to be determined, the sound attenuation of the hearing protector must be considered, for each individual and in consideration of the specific situation. The sound attenuation of a hearing protector is determined in the laboratory during the type examination and is stated by the manufacturer on the packaging. These values are however averaged values from measurements involving 16 test subjects. They do not therefore indicate the sound attenuation actually attained in individual cases. The scatter of the measured values between the test subjects is taken into account by statement not only of the mean of the series of measurements, but also of the assumed protection value (APV), which is the mean minus the standard deviation. Statistically, this sound-attenuation value is attained or exceeded on average for 84% of the users.

Besides these variations in the attenuation between test subjects under laboratory conditions, even greater deviations occur during use at work. During the type examination, the testing manager ensures that the test subjects fit or insert the hearing protector correctly. This is important primarily in order to ensure comparability between the sound attenuation values for products the protective action of which is measured using different groups of test subjects or by different laboratories. The attenuation possible under ideal conditions attained by each product is therefore measured in this procedure. Since the hearing protectors are not generally fitted or

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[1] the corresponding exposure limit value according to the EC-directive

inserted with the same care when used in plants, a lower sound attenuation is to be anticipated during use under realistic conditions.

Various international studies have shown that frequently, only very low effective sound-attenuation values are attained in practice [2; 3]. One of these projects was conducted in 1989 by the (then) BG Institute for Occupational Safety (BIA) [4]. Based upon the deviations identified in this older study between the sound-attenuation values measured in the laboratory and those measured in plants, derating values were defined. Following specification by the "Personal protective equipment" (PPE) expert committee of the German Social Accident Insurance (DGUV), these derating values have been considered in the selection of hearing protectors, e.g. in BG Rule 194 [5]. In other words, these values must be subtracted from the sound attenuation stated by the manufacturer (HML values for high, medium and low-frequency noises). The value for ear-plugs was 9 dB, for ear-muffs 5 dB and for custom moulded ear-plugs 3 dB.

Other countries have likewise developed methods by which allowance can be made during the selection of suitable hearing protectors for the poorer sound attenuation in the field (see Chapter 3). For example, double the standard deviation can be subtracted from the mean of the attenuation measured in the laboratory; this results in a higher percentage of users actually attaining this value. As an alternative to subtracting a fixed value, e.g. 9 dB for ear-plugs, a fraction of the sound attenuation measured in the laboratory can be employed as a field value, e.g. 50% for ear-plugs.

The present study was prompted by the question of whether the derating values for field use determined in the first BIA study are still valid, since some of the products studied at that time are no longer on the market. In consideration of the newly introduced maximum permissible exposure value, in particular, it appeared appropriate to review the derating values. Furthermore, the first study did not examine any custom moulded ear-plugs, since these products were still new at that time; they have since been adopted increasingly widely, however. For these reasons, the PPE expert committee recommended to the BGIA that the sound attenuation of hearing protectors in the field be studied. This is apparently the first time that an institution in any country has repeated a study of its own on this subject under comparable conditions.

The project was conducted in conjunction with the BG in the metalworking industry in Northern and Southern Germany. It had the support of the following statutory accident insurers (German Berufsgenossenschaften, BGs):

- BG in the mechanical engineering and metalworking industry
- BG in the building industry
- BG in the ceramics and glass industry

In the study, over 800 data records on over 20 different hearing protectors were obtained during a period of two years. The measurements were conducted directly in the plants. An audiomobile provided by the BG in the metalworking industry in Northern and Southern Germany and suitably converted by the BGIA was used for this purpose. For interpretation purposes, a distinction is drawn between ear-muffs and ear-plugs. The ear-plugs in turn are divided into products formable by the user prior to use, pre-formed ear-plugs, headband ear-plugs and custom moulded ear-plugs.

2 Reasons for the reduced sound attenuation in the field

In accordance with the PPE-Directive 89/686/EEC, hearing protectors must be tested by an independent third party (a "notified body") for their observance of the essential health and safety requirements before they may be placed on the market. The acoustic properties (sound-attenuation values) attained in this test must be stated by the manufacturer on the smallest commercial packaging unit. These attenuation values are used in order to check observance of the maximum permissible exposure values and for the selection of hearing protection products which are suitable for the noise situation in question.

In practice, however, the sound-attenuation level attained by the hearing protectors is normally substantially lower than the value by which they are characterized, depending upon the hearing protector type, the user's behaviour, and other objective factors.

For individual hearing protector types, the following have been found to be the main causes of the sound attenuation in the field differing from that attained in the type examination:

2.1 Ear-muffs

- The headband has aged.
- The cushions are aged or damaged.
- The user has very dense hair.
- The user wears earrings.
- The user wears glasses or protective goggles (particularly with thick earpieces).
- A respiratory protection device must be worn in addition to the ear-muff.
- The ear-muffs are reversed (right/left or top/bottom, according to the design.
- The user wears the band behind the head or under the chin rather than over the head.
- The cushions have become intended during storage.

- A safety helmet unsuitable for use in combination with this special type of ear-muffs is worn.

2.2 Ear-plugs

- The ear-plugs fail to fill the ear canal; an incorrect size is selected.
- The ear canal is too narrow for the ear-plug to be pushed into a firm seating position.
- The ear canal curves sharply.
- The ear-plugs are too cold or too old, i.e. not sufficiently elastic, and fail to adjust completely to the ear canal.
- The ear-plugs expand too rapidly when inserted.
- After inserting the ear-plugs into the ear canal, the user does not locate them sufficiently long with the finger to allow them to expand fully.
- Some flanged ear-plugs have only two flanges, which fail to seal all shapes of ear canal reliably. Problems particularly occur when the cross-section of the ear canal is strongly elliptical.

2.3 Headband ear-plugs

- The ear-plugs are seated on the ear canal only with light headband force.
- The ear-plugs slip out because the headband is too wide.
- The band is not positioned such that pressure is exerted perpendicular to the seating surface on the ear.
- The band has become distorted in storage.

2.4 Custom moulded ear-plugs

- Following use of the ear-plugs over one or more years, the ear canal has widened.
- The new product exhibits leakage [6].
- A leakage test has not been performed.

- A lack of marking and a short stub lead to left and right-hand ear-plugs being reversed.
- The pressure on the skin of the ear canal displaces the fluid in the tissue.
- Movements of the head, chewing, etc. cause additional leakage.

Particular problems arise with ear-plugs, especially formable products. If they are not properly rolled and compressed, they cannot be inserted sufficiently far into the ear canal, and may then slip out again partly or completely, with the result that the sound attenuation measured in the type examination is not attained.

A further factor with a major influence on ear-plugs which must be formed beforehand is the time required for the ear-plug to expand within the ear canal, i.e. the time before it has assumed a stable position and has seated such that it is sound-tight. This time ranges from 30 seconds to two minutes, depending upon the product. If the ear-plug is not located sufficiently long in the ear canal, expansion of the material may cause it to slip out again.

The expansion time of polyvinyl chloride (PVC) ear-plugs varies widely according to the ambient temperature. This may lead to time delays when the ear-plugs are inserted at low temperatures. Conversely, polyurethane (PU) ear-plugs may expand too quickly; their insertion requires a lot of practice, particularly with narrow ear canals.

The effective sound attenuation in practice is also reduced when the hearing protector is removed temporarily, for example owing to communication problems during telephone calls or during conversation in working areas with noise levels of ≥ 80 dB(A).

3 Methods for consideration of the reduced sound attenuation in the field

In order for consideration to be given to the reduction of the sound attenuation in the field, which has been demonstrated in various studies, a number of different approaches are applied in various countries. Since European legislation (e.g. the 2003/10/EC Noise at work Directive) also fails to specify binding provisions, the use of derating values to adjust the laboratory sound-attenuation values for the selection and use of hearing protection is at the discretion of the individual countries.

The overview shown here is based upon a survey conducted in 2007 by the Institut National de Recherche et de Sécurité (INRS) [7] among hearing protection experts in the Member States of the European Union and in certain other countries (Switzerland, Canada, the USA and Australia). The feedback received is summarized below according to the various methods used. The INRS received no response from Denmark or Austria to its inquiry.

For use in the field, the majority of countries apply the laboratory sound-attenuation values without correction. These countries include Sweden, Spain, Slovakia, Finland and Australia.

Some countries subtract fixed derating values (in dB) from the laboratory sound attenuation. This means that the sound energy which is able to pass owing to incorrect use is increased for all products by the same factor, irrespective of the sound attenuation measured for the product concerned in the laboratory. For example, a corrective reduction of 3 dB corresponds to a doubling of the sound energy acting upon the ear. Countries taking this approach include the United Kingdom, which reduces the attenuation values for all hearing protector types by 4 dB; and Germany and Switzerland, where the derating values differ according to the hearing protector type. At the time of the INRS survey, Germany and Switzerland used the values from the first BGIA study [4], i.e. 9 dB for ear-plugs and 5 dB for ear-muffs. In addition, a corrective value of 3 dB was applied in Germany for custom moulded ear-plugs.

Another method, which is applied in the USA [8] and Canada and is planned in Italy, reduces the sound attenuation in dB of each product by a certain percentage. The reference values used in Europe (SNR – single number rating) and the USA/Canada (NRR – noise reduction rating) differ, however. The following are assumed for the resulting attenuation values: 0.5 x SNR and 0.5 x NRR for ear-plugs; 0.75 x SNR and 0.75 x NRR for ear-muffs; and 0.3 x SNR and 0.3 x NRR for custom moulded ear-plugs.

Since neither of the two methods discussed up to this point considers the characteristics of the individual product, an alternative approach followed in Italy and Portugal is for the confidence interval for the sound attenuation to be increased. For this purpose, the parameters for the attenuation (APV, HML values or SNR) are calculated with a safety margin not of one standard deviation, but of two or three. This results in the proportion of users attaining or exceeding the stated value for the attenuation rising from 84% to 97.7 and 99.9% respectively. If a hearing protector now exhibits major standard deviation in the laboratory measurements, this standard deviation leads to a stronger reduction in the sound attenuation during application in the field.

France recently began implementing a combination of these methods [9]: double the standard deviation and additional deratings according to product type are subtracted from the mean of the sound attenuation measured in the laboratory. The derating values are 5 dB for ear-muffs, 7 dB for ear-muffs attached to a helmet, 10 dB for ear-plugs and 5 dB for custom moulded ear-plugs.

The final method presented here is that commonly used in the USA and set out in an ANSI standard (ANSI, American National Standard Institute). In this method, the type examination is not conducted with experienced test subjects who fit or insert the hearing protectors under the supervision of a testing manager, but with inexperienced persons. These persons are not familiar with the measurement method and are provided only with the user information for the product concerned. The thinking behind this method is that the test subjects use the hearing protectors as incorrectly as their counterparts in practice. As is to be expected, this method leads to lower mean sound-attenuation values and greater scatter. The product characteristics which can be attained under optimum conditions are not measured.

Plans are for this method to be adopted in Quebec.

4 Laboratory measurement as part of the type examination

During the mandatory type examination, an independent body notified for hearing protectors also determines the sound attenuation of the product. A subjective method based upon DIN ISO 4869-1 [10] and involving test subjects is employed for this purpose. Measurement of the sound attenuation is based upon measurement of the hearing threshold of a test subject with and without hearing protector. The difference between these two thresholds is the attenuation of a sound brought about by the hearing protector at the test frequency in question. The test arrangement and procedure used at the BGIA are described below.

Test signals with a one-third octave bandwidth at the mid-octave frequencies of 63 Hz (not mandatory), 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz and 8 kHz is employed and is produced by a test-signal generator. A step attenuator is able to adjust the signal automatically. The test standard specifies a diffuse sound field at the head of the test subject. This is generated by four loudspeakers arranged tetrahedrally around the test subject's seat in a semi-soundproof anechoic chamber. The first test signal is that at 1 kHz, this being the frequency most easily perceived. It is followed by increasing frequencies up to 8 kHz, and then by the signals at 500 Hz falling to 63 Hz.

The hearing threshold is determined by a computer-driven bracketing method in which the sound level is increased in steps until the signal is perceived by the test subject. The latter confirms perception by pressing and holding down a button, which in turn causes the level to be decreased until the test subject can no longer hear the signal, and releases the button. The step width determined by the control program is reduced from an initial level of 8 dB through 3 dB and 2 dB to 1 dB, enabling the hearing threshold to be narrowed down with increasing precision.

Check mechanisms within the program monitor during measurement whether the progression of the sound level indicated by the test subject is plausible. Reversal points which are improbable are ignored. The upper and lower reversal points for example must not be more than 10 dB apart. In addition, upper reversal points which lie below a lower threshold are rejected. Should a measurement at a given frequency last too long, the program is interrupted, allowing the testing manager to instruct the test subject again. External intervention during the procedure is not otherwise possible.

At each hearing threshold measurement and test frequency, the hearing threshold is bracketed four times and the corresponding signal level read off when the subject presses the button (i.e. "signal heard") and releases it again (i.e. "signal no longer heard"). The arithmetic mean of these eight levels is saved as the respective hearing threshold.

5 Measurement of the sound attenuation in the plants

The experimental procedure of the present project is based closely upon the first study on the subject conducted in 1989 [4]. The objective was that of determining the sound attenuation of a hearing protector under realistic conditions in the plant itself. At the same time, the data obtained in this way were to be comparable with those obtained during type examination.

5.1 Measurement method in the audiomobile

As in the method described in Chapter 4, the hearing threshold of test subjects was also determined in the audiomobile with and without hearing protection. The difference between these two thresholds is the sound attenuation of the hearing protector in question. As far as possible, the measurement method and test arrangement (control program, test signal generator) employed were identical to those used in the laboratory for the type examination.

Owing to technical constraints (see Sections 5.2 and 5.3), only noises with a one-third octave bandwidth at the mid-octave frequencies of 250 Hz, 500 Hz, 1 kHz, 2 kHz and 4 kHz could be used as test signals. Here too, measurement began at 1 kHz, followed by the high frequencies, and finally by the two low-frequency noises. Since the test subjects were not familiar with the measurement method, a test pass at 1 kHz was conducted prior to measurement proper. The course of the program and the plausibility tests during measurement were otherwise identical to the type examination.

5.2 Equipment of the audiomobile

The test arrangement was installed in the autumn of 2005 in a vehicle belonging to the BG for the metalworking industry in Northern and Southern Germany. The vehicle was an audiomobile with two test chambers, one of which had been converted for the study of hearing protectors (Figure 1, page 24).

The different parts of the audiomobile are isolated to different degrees against ambient noise. The control room is less well isolated than the chambers, which can be separated in addition from the rest of the vehicle during the actual performance of measurements by a sliding door. The sound attenuation of the test chambers is designed for the needs of audiometric check-ups (air-conduction measurement with headsets); it does not therefore meet the stricter requirements governing the back-ground noise level which apply to the hearing protector test in the laboratory.

Figure 1:
Inside view of the audiomobile: in the foreground, the control room; to the rear, the two audiometry test chambers. The right-hand chamber was equipped with loudspeakers for the sound-attenuation measurements.

The computer for monitoring the progress of the measurements was positioned in the control room, the equipment for generation of the test signal in the room in front of the test chambers. Loudspeakers were also installed in the test chamber for generation of the sound field. Ideally, the sound field at the test subject's head should be diffuse, as required in the DIN ISO 4869-1 [10] test standard for hearing protectors; this is how-ever difficult to attain in the small room with its floor area of approximately 1 m^2. As a compromise, a symmetrical arrangement was selected in which a vertical bank of four loudspeakers was installed in a corner (Figure 2). For the purpose of measurement, the test subjects were required to sit in the opposite corner facing the loudspeakers. The location of the loudspeakers and the high-impedance surfaces of the chamber produced an acceptable sound field. For low frequencies (in this case 250 Hz), an additional bass loudspeaker was required; it was installed under the seat, since the directional dependency in this frequency range is not strong.

Figure 2:
View of the converted audiometry chamber from outside; the test subject was seated facing the loudspeaker bank (see arrow on floor). The bass loudspeaker is located beneath the seat.

5.3 Comparison with the laboratory method to DIN ISO 4869-1

Owing to the geometric and acoustic constraints in the audiomobile, deviations from the laboratory method are inevitable. The most important of these concern the characteristic of the sound field, extraneous background noise, and the test subjects' lack of experience with the measurement method.

As described in Section 5.2, it was not possible to generate a diffuse sound field corresponding to the standard in the chamber of the audiomobile. Since the "open" hearing threshold (hearing threshold without hearing protector) is also dependent upon the angle of incidence of the sound, the sound field can generally be expected to have an influence upon the measured attenuation. The extent to which this is the case when hearing protection is worn was studied by comparative measurements with one type of ear-plug (see Section 6.3, page 30).

Background noise from outside, and to a substantially lower degree also from the control room, could not be avoided during many measurements. The most important sources of noise were traffic within the plant, such as fork-lift trucks, conversations in the vicinity of the audiomobile, and rain. Conversations and people walking within the control room were also audible within the test chamber, resulting in the test subject easily being distracted. The greatest effect is that of background noises during measurement of the "open" hearing threshold, since these displace the threshold to higher levels. Conversely, when hearing protection is worn, the influence is lower; the sound attenuation, i.e. the difference between the two hearing thresholds, is thus reduced.

A further difference to the laboratory measurement under defined conditions is the test subjects' lack of experience with the test procedure. Bracketing of the hearing threshold generally necessitates some experience; a test pass at a frequency of 1 kHz was therefore completed prior to measurement proper. The results nevertheless exhibit greater uncertainty than the laboratory values. In particular, the first frequencies of the hearing threshold measured with hearing protector worn could be unreliable. This influence of the test subject collective upon the sound attenuation was also studied by means of comparative measurements (see Section 6.3).

Finally, mention should be made of the test subjects' physical suitability. The test standard specifies that the subjects should have healthy hearing and may exhibit only minor deviations from the reference hearing threshold. These criteria were of course not necessarily met during the field study, nor could they be checked. Hearing loss or complaints such as tinnitus are possible and indeed likely among persons exposed to noise.

5.4 Questionnaire

A two-part questionnaire was completed for each test subject. In the first part, the test subject was questioned regarding, for example, their hearing ability and hearing protectors. The second part was completed by the testing manager during the measurements. The testing manager paid particular attention to background noise and to uncertainty on the part of the test subject during bracketing of the hearing threshold, in order to enable implausible data to be identified during interpretation.

5.5 Organization and procedure of the measurements

All measurements were organized and conducted by the four BGs involved in the project. The majority of measurements were organized by staff and audiometrists at the BG in the metalworking industry in Northern and Southern Germany. Member companies willing to take part in the project had to be found in advance. Since the measurements had to be conducted during working hours and could not be performed in place of the routine check-ups for noisy workplaces, the parties responsible in the plants had to be motivated to participate. One incentive was that of obtaining information on the wearing behaviour of hearing protection in practice following completion of the project.

An attempt was made to select plants with the largest possible groups of employees using the same hearing protection, since only sufficiently large random samples deliver meaningful results. For some hearing protector types (custom moulded earplugs and ear-muffs) for which only a small number of data records could initially be obtained, the BGs' labour inspectors approached companies directly.

The measurements were conducted by audiometrists from the BGs who had been instructed by the BGIA in the use of the test apparatus. Ideally, the audiomobile was to be set up at a quiet location on the plant site in order for interference from background noise to be avoided as far as possible. The employees were informed in advance of the measurements and were to proceed directly from their workplace to the audiomobile. For this purpose, they were required to wear their hearing protection exactly as in the plant. Altogether each measurement – involving instruction, completion of the questionnaire and performance of the two hearing threshold measurements (with and without hearing protector) – lasted approximately 30 minutes for each person.

6 Interpretation of the measurement results

This chapter describes the procedures for interpretation of the data measured in the audiomobile. The results can be found in Chapter 7.

6.1 Creation of a database

In order for the data measured by various testers over a longer period to be managed comprehensibly, the BGIA set up a database. The audiometrists from the BGs sent the measured data (on data media) and the questionnaires to the BGIA which collected them centrally for interpretation.

The database had the advantage that each measurement could be linked to the associated questionnaire, enabling the data on the hearing protector and the user to be displayed directly on the screen for each sound-attenuation characteristic, together with the notes made by the testing manager.

Since each product had already been assigned a code number for measurement, all data received from different plants for a particular hearing protection product could be grouped automatically. The index of all data records showed the products for which the random sample was not yet sufficiently large, and the hearing protector types to which particular attention was to be paid during subsequent measurements. Data records with an insufficient number of measurements could not be considered for interpretation.

6.2 Rejection of implausible data records

Prior to interpretation, the data were reviewed for plausibility in order for clearly illogical values to be rejected. Possible sources of error during measurement were background noise and uncertainty or inexperience on the part of the test subjects (see Section 5.3).

Following input of the measured values into the database, the data from the questionnaire (Section 5.4), in which the testing manager had noted irregularities during measurement, were available for each data record.

All data records were displayed graphically for each product (sound attenuation plotted against frequency) and the characteristics identified which exhibited improbably high or low sound-attenuation values. Values of < -5 dB (improved hearing with hearing protection) or > 50 dB were considered improbable. Characteristics containing outliers (discrete spikes) were also considered critical. A decision was taken on a case-by-case basis, in consideration of the information on the questionnaire, whether to reject an unsafe data record or to include it in the interpretation. As a result, 19 out of 602 data records were excluded from the interpretation.

6.3 Determining of correction values for the sound field in the audiomobile

Before the data measured in the audiomobile could be compared with the sound-attenuation values measured in the laboratory, the influence of the test arrangement (measurement of the attenuation values in the audiomobile) upon the results had to be determined, and a means found for correction of this effect. As described in Section 5.3, the sound-attenuation measurements conducted in the audiomobile must be expected to exhibit systematic deviations from the values measured in the laboratory. In order for this influence to be quantified and thus also corrected, comparative measurements were conducted at the BGIA between the laboratory and the audiomobile.

In principle, the two situations (laboratory and audiomobile) differ in three aspects: the characteristic of the sound field, the reliability of the test subjects in the hearing threshold measurement, and fitting of the hearing protector. Since the last of these aspects is the actual objective of the present study, the two other influencing factors had to be eliminated from the data as far as possible. Since the influence of the sound field differs between ear-plugs and ear-muffs, a distinction was drawn between these two product types for the specification of the necessary correction values.

In order for the correction values for ear-plugs to be determined, four different measurements were conducted with a headband ear-plug: in the laboratory sound field and in the audiomobile, in each case with experienced and inexperienced test subjects. In this context, "inexperienced" means that the test subjects were not familiar with the test method for measurement of the hearing threshold. The testing manager checked that the hearing protector was fitted correctly. All persons (16 per group) were employed at the BGIA. Of primary interest was whether the conditions for in-plant measurements (sound field and inexperienced test subjects) would also change the mean of the sound attenuation, or merely increase the standard deviation of the random sample.

Figure 3 shows the means of the four measurements for the sound attenuation, Figure 4 (see page 32) the associated standard deviations. Systematic differences are evident at several points. If the two groups of test subjects for one measurement site are compared (i.e. the solid symbols on the graph compared to the corresponding open symbols), the measurements in the laboratory on experienced test subjects are seen to yield higher attenuation values at all frequencies, with a maximum difference of approximately 6 dB. A similar effect is evident for the audiomobile; the attenuation at low frequencies is virtually identical, and substantially better for the experienced test subjects only upwards of 1 kHz (max. approx. 5 dB). The standard deviations, which lie in the range between 5 and 7 dB for all series of measurements, are somewhat greater for the experienced test subjects in both the laboratory and audiomobile.

Figure 3:
Mean of the sound attenuation, from control measurements conducted with a headband ear-plug in the laboratory and in the audiomobile, on 16 experienced and 16 inexperienced test subjects in each case

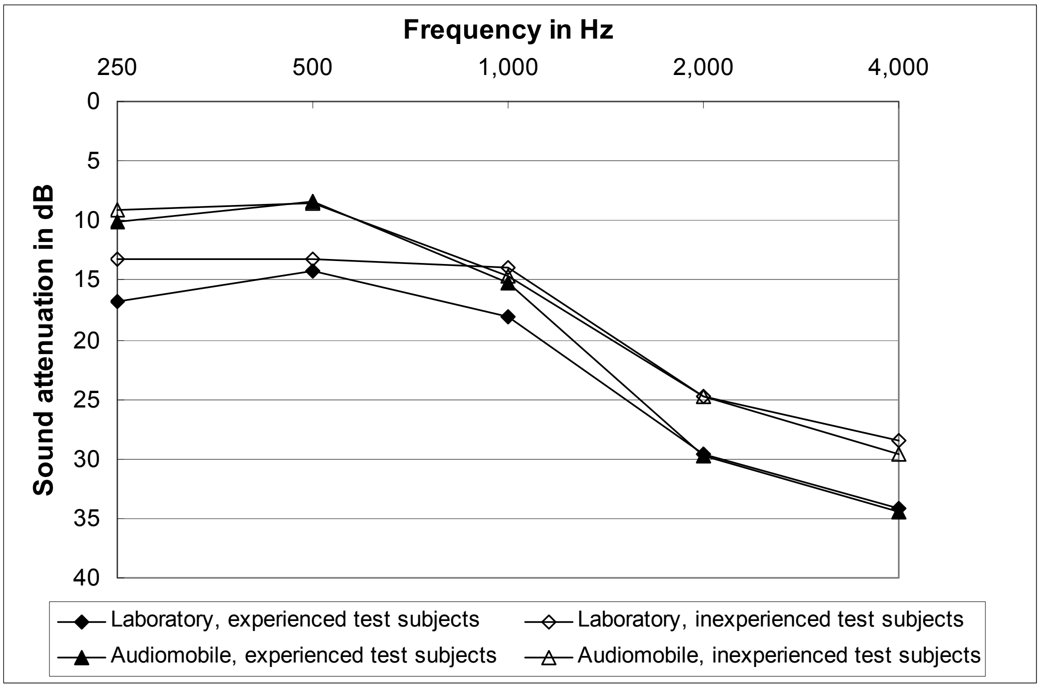
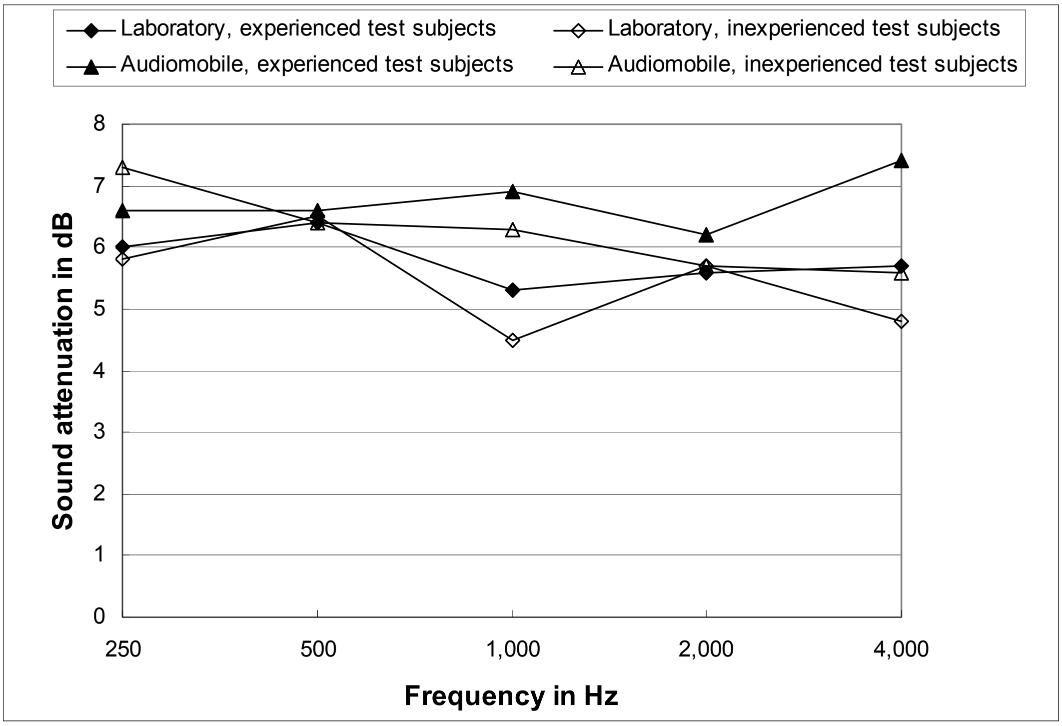


Figure 4:
Standard deviation of the sound attenuation, from control measurements conducted with a headband ear-plug in the laboratory and in the audiomobile on 16 experienced and 16 inexperienced test subjects in each case (cf. Figure 3)



When the two measurement sites are compared for a group of test subjects, i.e. squares compared with triangles on the graph, the experienced test subjects in the laboratory exhibit attenuation values for the low frequencies which are higher by up to 7 dB, whereas no difference is observed at high frequencies. A similar observation is made for the inexperienced test subjects. The standard deviations are greater in the audiomobile than in the laboratory, which can probably be attributed to the extraneous background noise.

In order for the effects during the in-plant measurements which mask the influence of fitting or insertion of the hearing protectors to be corrected as effectively as possible, the two data records for experienced test subjects in the laboratory and inexperienced test subjects in the audiomobile must be compared. For the difference between the means (between the laboratory and the audiomobile), the values are shown in Table 1. The deviation is somewhat greater at low frequencies, which can probably be attributed to the influence of background noise (see Section 5.3).

Table 1:
Correction values for the sound attenuation of ear-plugs, from measurements with a headband ear-plug involving experienced test subjects in the laboratory and inexperienced test subjects in the audiomobile

Frequency in Hz	250	500	1,000	2,000	4,000
Difference in the mean of the sound attenuation in dB	7.7	5.7	3.5	4.8	4.5

Since these values were calculated from means of standard deviations, they also exhibit uncertainty in principle, i.e. a standard deviation; this was however not taken into account during interpretation. The reasons for this are discussed in Section 6.4. Nevertheless, a model calculation in Table 4 (page 37) shows the effect which consideration of the standard deviation would have.

Corresponding correction values for ear-muffs were to be determined in a second series of measurements. For this purpose, measurements were conducted at the Mainz site of the BG in the metalworking industry in Northern and Southern Germany on 14 employees who were not familiar with the measurement method. The testing manager did however check proper fitting of the hearing protector. Figure 5 (page 34) shows the mean and the standard deviation of each of these control measurements in the audiomobile and the corresponding values from the type examination. The differences in the sound attenuation for the individual frequencies are listed in Table 2 (page 34). In contrast to ear-plugs (Table 1), the results show a strong correlation between the frequency and the differences in sound attenuation: the values fall from over 8 dB at 250 Hz to 0 dB for the two highest frequencies of 2 and 4 kHz. Since attention was paid to correct fitting of the hearing protector with the test subjects in the control group, these differences can be attributed to effects caused by the sound field and extraneous background noise.

For the purpose of interpretation, the respective correction values for ear-plugs and ear-muffs were added to the sound attenuation measured in the audiomobile. This is to result in any difference between the values measured in the laboratory and the audiomobile being attributable only to the hearing protector not being properly fitted.

Figure 5:
Mean (M) and standard deviation (SD) of the sound attenuation for an ear-muff, measured on experienced test subjects in the laboratory (type examination) and on inexperienced test subjects serving as a control group in the audiomobile

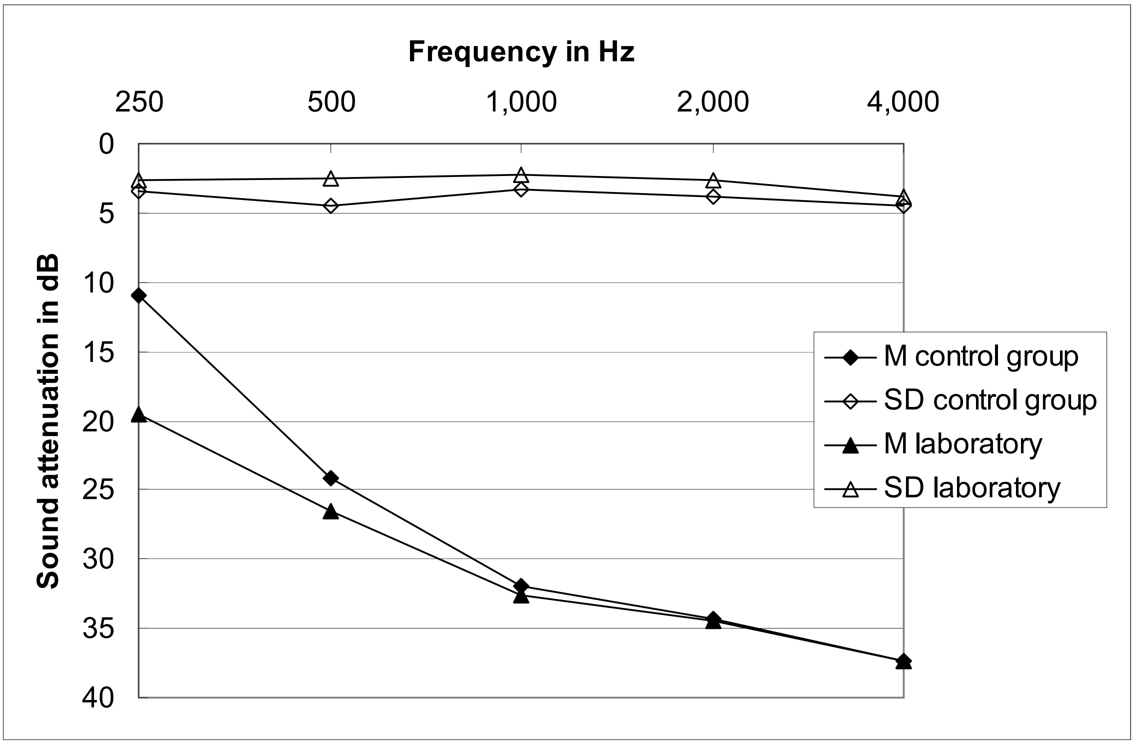


Table 2:
Correction values for the sound attenuation of ear-muffs, from measurements involving experienced test subjects in the laboratory and inexperienced test subjects in the audiomobile

Frequency in Hz	250	500	1,000	2,000	4,000
Difference in the mean of the sound attenuation in dB	8.6	2.4	0.7	0.0	0.0

6.4 Target dimension: difference in the mean of the sound attenuation and of the APV

The objective of the study was to determine the sound attenuation of hearing protectors in use at work. Of itself, however, this does not indicate which of the variables which can be deduced from the measured values best describes the difference between sound attenuation in the laboratory and in the field. This section is to illustrate the process of interpretation and the possible target dimensions, with reference to an example. The data record relates to an ear-plug formable prior to use, for which

25 in-plant measurements were conducted (Figure 6 and Table 3). Data records with implausible sound-attenuation values were first rejected (see Section 6.2, page 29).

Figure 6:
In-plant measurements (n = 25) of an ear-plug which must be formed prior to use

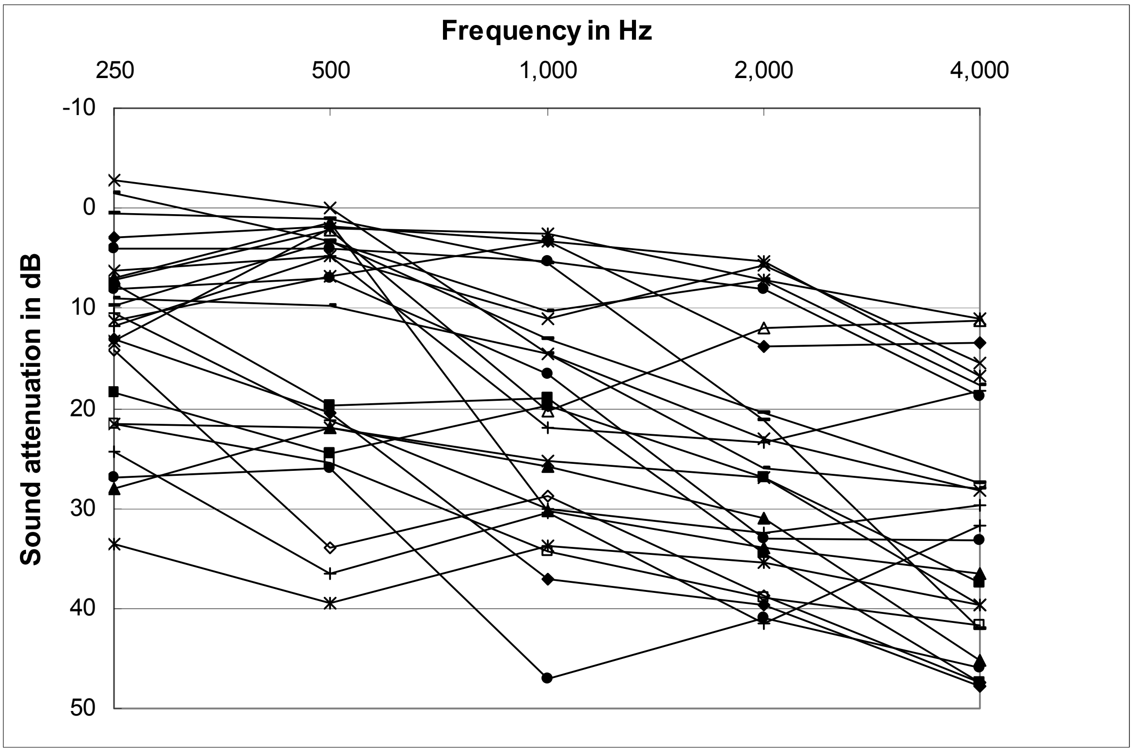


Table 3:
In-plant measurements (n = 25) of a formable ear-plug,
mean and standard deviation (measured values in steps of 0.25 dB)

No. of the data record	Sound attenuation in dB at frequencies in Hz				
	250	500	1,000	2,000	4,000
1178	13.0	20.5	37.0	39.75	47.75
1179	7.5	19.75	19.0	34.5	47.5
1180	28.0	22.0	25.75	31.0	45.25
1199	-2.75	0.0	14.5	23.0	28.25
1200	11.25	6.75	3.25	5.25	16.75
1201	4.0	4.0	5.25	8.0	18.75
1202	24.25	36.5	30.5	41.5	31.75

Table 3: Continued

No. of the data record	Sound attenuation in dB at frequencies in Hz				
	250	500	1,000	2,000	4,000
1203	-1.5	3.25	10.25	7.25	17.75
1204	0.5	1.0	5.5	21.25	42.0
1195	14.25	34.0	28.75	38.75	47.5
1196	21.5	25.5	34.25	39.0	41.75
1197	7.25	2.25	20.25	12.0	11.25
1198	21.5	22.0	25.25	27.0	39.75
1280	33.5	39.5	33.75	35.5	39.75
1279	27.0	26.0	47.0	41.0	46.0
1278	10.5	21.25	30.0	32.5	29.75
1277	9.0	9.75	14.5	26.0	28.0
1276	9.75	3.25	13.0	20.5	27.5
1275	3.0	1.75	3.25	13.75	13.5
1274	18.5	24.5	19.75	27.0	37.5
1273	7.0	1.5	30.25	34.0	36.5
1272	6.25	4.75	11.0	5.65	15.5
1271	13.25	2.0	2.5	7.25	11.0
1270	8.0	7.0	16.5	33.0	33.25
1269	11.75	4.75	22.0	23.5	18.25
Mean	12.3	13.7	20.1	25.1	30.9
Standard deviation	9.4	12.5	12.0	12.2	12.5

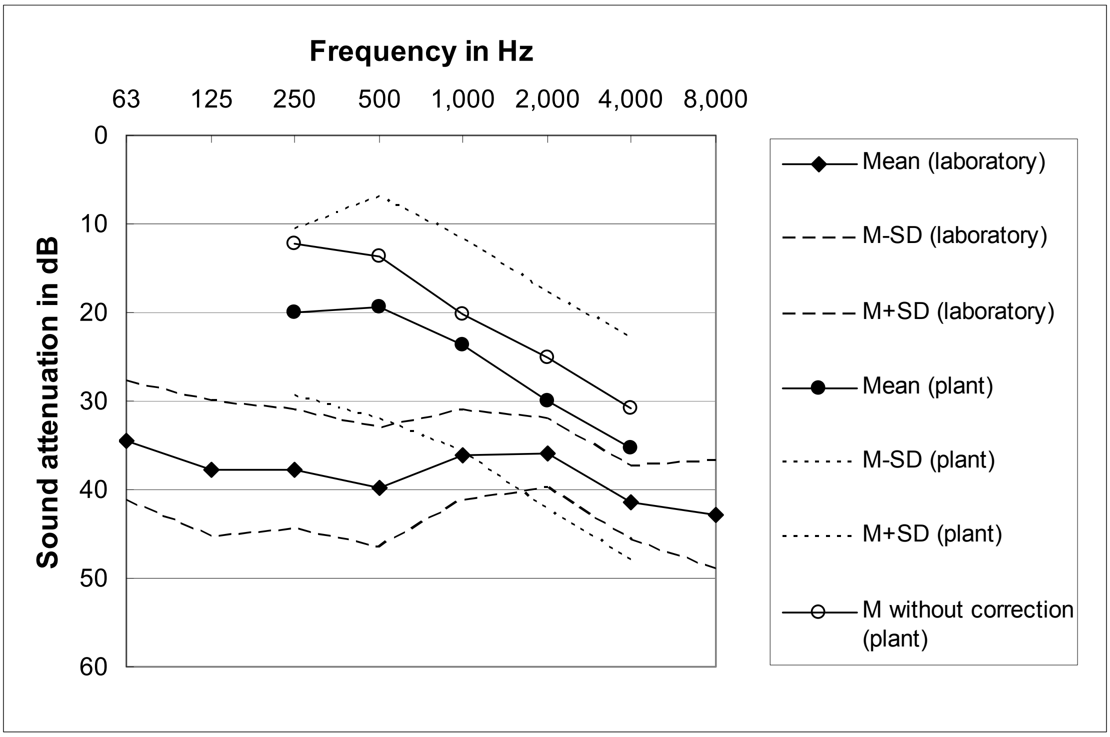
Table 4 shows the further interpretation steps for calculation of the means from these 25 measurements. Only the calculation steps for the **means** will be discussed in the first instance. These are increased by the correction values explained in Section 6.3 (Line 1 + Line 3 in Table 4). These corrected means (= Line 5 in Table 4) can now be compared directly (see Line 14) with the means for the corresponding laboratory data (see Line 11), either broken down by frequency, or averaged (last value in the line). Since only five of the eight usual test frequencies could be measured, it is not possible to determine the field derating values completely broken down by frequency. The final result for each type of hearing protector is thus only the mean across the tested frequency range, which in the example shown here is approximately 13 dB.

Table 4:
Example procedure for interpretation using the data from Table 3

Line		Frequency in Hz					
		250	500	1,000	2,000	4,000	
Mean and standard deviation from 25 in-plant measurements							
1	Mean	12.3	13.7	20.1	25.1	30.9	
2	Standard deviation	9.4	12.5	12.0	12.2	12.5	
Correction values in accordance with Table 1 (page 33)							
3	Mean	7.7	5.7	3.5	4.8	4.5	
4	Standard deviation	9.4	9.1	8.2	8.0	8.0	
Corrected (standard deviation not considered)							
5	Mean (1 + 3)	20.0	19.4	23.6	29.9	35.4	
6	Standard deviation	9.4	12.5	12.0	12.2	12.5	
7	APV	10.6	6.9	11.6	17.7	22.9	
Corrected (Standard deviation considered)							
8	Mean	20.0	19.4	23.6	29.9	35.4	
9	Standard deviation	13.3	15.5	14.5	14.6	14.9	
10	APV	6.7	3.9	9.1	15.3	20.5	
Type examination values measured in the laboratory							
11	Mean	37.8	39.8	36.2	35.9	41.5	
12	Standard deviation	6.7	6.8	5.1	3.9	4.2	
13	APV	31.1	33.0	31.1	32.0	37.3	
Difference							Mean
14	Mean (11 - 5)	17.8	20.4	12.6	6.0	6.1	12.6
15	APV	24.5	29.0	22.0	16.7	16.8	21.8
16	APV alternatively	20.6	26.1	19.5	14.3	14.4	19.0

For all products studied, the means from the in-plant measurements are lower than those from the laboratory measurements. If the individual frequencies are considered, the strongest effect is observed at the low frequencies, as is typically the case with leakage caused by poor fitting. Figure 7 shows the values from Lines 1, 5 and 11 of Table 4 in diagrammatic form. The effect of the sound-field correction in Table 1 is also shown (data record with open circles).

Figure 7:
Data from Table 4 for a formable ear-plug; mean and standard deviation of the random samples from laboratory and in-plant measurements. The sound-field correction in Table 1 was not considered for the graph with the open symbols.



After the mean value of the sound attenuation, the **standard deviation** of the random sample is the second value of importance, since it reflects the scatter. This is also considered by declaration of the sound-attenuation values of hearing protectors in the form of the assumed protection value (APV). The APV is calculated from the mean of the measured sound attenuation minus the standard deviation. Assuming measured values of normal distribution, this value for the sound attenuation is at least attained for 84% of persons, the mean conversely only for at least 50%.

As is to be anticipated, the standard deviation in the in-plant measurements is generally higher than in the laboratory measurements, since the test subjects do not ensure correct fitting of the hearing protectors. Together with the reduced mean of the attenuation, this influences the APV for the measurements in the audiomobile. The difference between the APVs from laboratory and audiomobile measurements is thus generally greater than that between the corresponding means, since both effects which lead to poorer protective action (i.e. reduction of the APV) are taken into account. Table 4 shows the APV for the audiomobile measurement in Line 7 (Line 5 - Line 6), that for the laboratory measurements in Line 13. In this example, the total differences are therefore 19 dB for the APV (Line 16, last column) and approximately 13 dB for the mean.

Strictly speaking, adjustment of the attenuation values measured in the audiomobile by means of the correction values in Table 1 should also take their standard deviation into account (Line 4 in Table 4). Calculation with the law of error propagation from the data in Lines 2 and 4 yields the standard deviation in Line 9. This increases the standard deviation of the audiomobile data even further, leading to an even greater deviation between the APVs of 22 dB (Line 15, final column).

In order to make the field deratings more manageable with regard to their uncertainty, the "PPE" expert committee agreed the following convention:

Only the means are used during calculation of the field derating values produced from the difference between measurements in the laboratory and the audiomobile.

With this specified procedure, the deviation of the standard deviation between the field measurements and the laboratory measurements is ignored.

Further interpretation of the data from the audiomobile (averaging and error analysis) thus considers only the difference between the means.

6.5 Testing of the data records for normal distribution

Since the two variables of the mean and standard deviation are always used for interpretation of the data records, selected random samples were tested by way of example for whether the measured values conform to a normal distribution. Two methods were employed for this purpose: The data can be plotted on a probability paper, thereby permitting visual analysis of the distribution. Alternatively, the Kolmogorov-Smirnov test implemented in the SPSS statistics program (Version 15) was used which computes tests for normal distribution and outputs an associated confidence level.

For plotting on a probability paper, the measured attenuation values must be classified according to their magnitude. For each class, the relative frequency is then calculated, i.e. the proportion of data in each class. This yields the cumulative frequency, i.e. the proportion of data in each class or those below it. These values for the measured data record are then compared with the corresponding figures for a calculated normal distribution exhibiting the same mean and the same standard deviation as the random sample. In order for the distribution of the data to be illustrated graphically, the cumulative frequencies are plotted against the measured attenuation values. A special ordinate scale is employed in this case for the cumulative probability. The scaling is selected such that a normal distribution yields a straight line, making deviations of the measured values from it readily apparent.

The Kolmogorov-Smirnov test likewise considers the deviations of the measured data from a normal distribution which corresponds to the random sample in its mean and standard deviation. For this purpose, the cumulative frequencies are first determined for the random sample and the calculated normal distribution. For each measured value, the difference is calculated between the frequencies determined experimentally and by calculation. Maximum deviations are tabulated as a function of the random sample size and the required confidence level. Should a difference from the measurement exceed this value, the measured distribution at the selected confidence level is not normally distributed.

6.6 t-Test: significance of the deviations between laboratory and audiomobile

For testing of whether the difference between the two random samples from the laboratory and the audiomobile is significant, the SPSS statistics program was used to apply the t-test to the measured values from the audiomobile (separately for each test frequency). The test indicates the probability of the means of two random samples originating from the same population. In the case under consideration, this probability can be expected to be low, since the ways in which hearing protectors are worn in the laboratory and in the field differ significantly. The t-test of a random sample was employed, in which the mean from a random sample was compared with a test value. The test value was the sound-attenuation value measured in the laboratory minus the corresponding correction value from Section 6.3, since the discrete values were not available for the laboratory sound attenuation. 5% was selected as the significance level in the test.

Various different scenarios are possible. The values measured in the audiomobile may be higher or lower than those measured in the laboratory; the means may also exhibit a large difference or be very close. In this last case, the probability of a common population is high, and the two random samples should not then be considered different.

6.7 Averaging for specific types of hearing protector

The products studied in the measurements conducted in the audiomobile cover all available types of passive hearing protectors. These are:

- ear-plugs (foam) which must be formed prior to use
- pre-formed ear-plugs (flanged ear-plugs)
- headband ear-plugs
- ear-muffs
- custom moulded ear-plugs

Since the individual types differ in how well and how reliably they are typically used, the difference between the sound attenuation measured in the laboratory and that measured in the audiomobile was determined in this project for each type of hearing protector. For this purpose, the results for the products of a given type had to be averaged in a suitable manner.

Three values describe each random sample (data record for a particular hearing protector product): the size of the random sample (n_i) and (for each of the five test frequencies) the mean ($\overline{x_i}$) and the standard deviation (s_i) of the difference between the sound attenuation values measured in the laboratory and in the audiomobile. In order for these values to be considered, the differences in sound attenuation between the k various random samples for a given hearing protector type were averaged, weighted in accordance with the following formula [11]:

$$\overline{\overline{x}} = (\sum_{i=1}^{k} n_i\, \overline{x}_i / s_i^2)/(\sum_{i=1}^{k} n_i / s_i^2) \qquad (1)$$

Owing to the weighting with the size of the random sample and the standard deviation, random samples of larger size or with a lower standard deviation have a greater influence upon the final result.

This averaging is possible for each of the five test frequencies or for the mean across the frequencies. Recourse must be made to this value when the effect of the incorrect wearing of hearing protectors is to be described by a single figure. In the same way, the mean of the standard deviations over the five frequencies was employed as the corresponding standard deviation.

6.8 Consideration of the uncertainty

This section describes the uncertainties of the (final) results of interpretation. In principle, precise measurement of all values is not possible. In the case under consideration here, the values are the sound attenuations measured in the laboratory and the audiomobile, and the correction values for the influence of the sound field. All values are produced from random samples followed by averaging. The standard deviation describes the relevant scatter.

The sound-field correction is calculated from the difference between the sound attenuation in two different measurements. The uncertainty of this difference is calculated by application of the law of error propagation to the uncertainties of the two individual series of measurements. The resulting uncertainty is relatively large.

Since the objective of this study was to determine the sound attenuation attained in the plant, the uncertainty was considered only for the values measured in the plant. The uncertainty of the correction values is not therefore considered in the interpretation, with the result that the same standard deviation is assigned to the differences from the laboratory values which are adjusted (by the magnitude of the influence of the sound field) as to the measured raw data.

As described in the preceding section, the weighted mean over the differences in sound attenuation of the individual products was formed for each hearing protector type. This value characterizes a series of measurements which is formed by the merging of all values from the individual random samples. For this series of measurements, the weighted variance in the x values can be also be calculated by means of the following formula [11]:

$$s^2 = \frac{1}{n-1}\left[\sum_i (n_i - 1)s_i^2 + \sum_i n_i(\bar{x}_i - \bar{\bar{x}})^2\right] \qquad (2)$$

A further variable of interest is the standard error of the mean which is produced from this standard deviation *s* and the size of the overall series of measurements *n*:

$$s_{\bar{x}} = s / \sqrt{n} \qquad (3)$$

7 Results and discussion

7.1 Compilation of the results

Altogether, 829 data records were recorded, of which 583 were considered for interpretation. Results are thus available for 13 products; the largest random sample encompasses 88 measurements, the smallest 11.

The results are presented in the tables and graphs of the following sections. A general discussion follows in Section 7.1.5; further sections address particular aspects.

7.1.1 Overview of the data records – overall result

Table 5 shows the interpreted data records with the corresponding size of the random sample, broken down by hearing protector type. Formable ear-plugs – which must be formed before use – constitute the largest group, in terms of both number of products (5) and number of data records (262). Records for only two products of each of the other hearing protector types were interpreted. Three products in the category of custom moulded ear-plugs were studied; one random sample is however substantially smaller than the other two, and thus makes little contribution to the weighted mean.

Table 5:
Interpreted data records, by hearing protector type

Product name	Number of measurements
Formable ear-plugs	
Moldex Spark Plugs	88
E-A-R Classic II	74
Howard Leight MaxLite	37
Bilsom 303	38
Howard Leight MultiMax	25
Pre-formed ear-plugs	
E-A-R UltraFit	62
Moldex Rockets Cord	27

Table 5: Continued

Product name	Number of measurements
Headband ear-plugs	
Bilsom PerCap	30
E-A-R Flexicap (under-the-chin)	33
Ear-muffs	
Bilsom Viking V2	33
Custom moulded ear-plugs	
Sicom	60
Uvex HighFit F10	69
Sonus AS	11

Table 6 provides an overview of the overall result of the study. The averaged difference between the means of the sound-attenuation values measured in the laboratory and in the audiomobile is stated for each hearing protector type. The mean, the standard deviation and the standard error of the mean were calculated for this value (see Section 6.8, equations 1 to 3).

Table 6:
Averaged differences in the sound attenuation between the measurements conducted in the laboratory and in the audiomobile; SD: standard deviation of the mean; SE: standard error of the mean

Number of types	Number of data records	Averaged difference in the means	SD	SE
Formable ear-plugs				
5	262	7.8	10.9	0.7
Pre-formed ear-plugs				
2	85	5.0	9.7	1.0
Headband ear-plugs				
2	63	4.5	8.3	1.0
Ear-muffs				
1	33	3.0	---	---
Custom moulded ear-plugs				
3	140	6.0	9.0	0.8
$\sum$ = 13	**$\sum$ = 583**			

7.1.2 Difference in sound attenuation, by hearing protector type

Tables 7 to 16 show the results for the individual products, listed separately by hearing protector type. The first table for each product group contains the difference between the sound attenuation measured in the plant/audiomobile and in the laboratory, averaged over the five test frequencies. For the purpose of comparison, these differences are stated both for the mean of the sound attenuation and for the APV (assumed protection value) (cf. Section 6.4). The difference for the APV is substantially greater, since the greater standard deviation of the field measurements is also considered in this case. This table also lists the standard deviation averaged over the frequencies for each product. This value is required for weighted averaging of the differences in sound attenuation. The resulting mean, together with standard deviation (SD) and standard error (SE), is the final result for a hearing protector type.

The second table for each hearing protector type shows the difference in the sound attenuation for all products, as a function of the frequency. The associated mean and standard deviation were formed for the individual random sample in this case.

Table 7:
Formable ear-plugs: deviation from the laboratory sound attenuation, averaged over the frequencies

Product name	**Number of data records**	**Averaged difference in the means**	**SD of the random sample**	**Difference in the APV**
Moldex Spark Plugs	88	8.9	11.4	14.3
E-A-R Classic II	74	2.8	9.3	8.0
Howard Leight MaxLite	37	10.5	10.1	15.1
Bilsom 303	38	11.9	9.4	14.0
Howard Leight MultiMax	25	12.6	11.8	19.0
	∑ = 262			
	Mean	**7.8**		
	Standard deviation	**10.9**		
	SE of the mean	**0.7**		

Table 8:
Formable ear-plugs: differences in the means of the sound attenuation (between laboratory and plant) for the five frequencies studied

	Frequency in Hz				
	250	**500**	**1,000**	**2,000**	**4,000**
Moldex Spark Plugs					
Mean	12.5	13.1	9.4	3.8	5.4
Standard deviation	10.8	11.2	13.0	10.4	11.4
E-A-R Classic II					
Mean	5.9	5.5	1.3	0.3	1.2
Standard deviation	8.4	8.8	11.6	9.0	8.5
Howard Leight MaxLite					
Mean	18.1	18.1	15.0	1.3	-0.2
Standard deviation	9.3	11.1	8.4	11.8	9.8
Bilsom 303					
Mean	18.6	19.5	12.4	3.8	5.1
Standard deviation	8.9	10.0	10.0	8.3	9.8
Howard Leight MultiMax					
Mean	17.9	20.4	12.6	6.0	6.1
Standard deviation	9.4	12.5	12.0	12.2	12.5
Averaged over all products					
Mean	12.5	12.3	9.5	2.5	2.9
Standard deviation	10.7	11.9	12.5	10.2	10.5
SE of the mean	0.7	0.7	0.8	0.6	0.7

Table 9:
Pre-formed ear-plugs: deviation from the sound attenuation measured in the laboratory, averaged over the frequencies

Product name	**Number of data records**	**Averaged difference in the means**	**SD of the random sample**	**Difference in the APV**
E-A-R UltraFit	58	5.2	9.2	7.6
Moldex Rockets Cord	27	4.4	10.7	10.0
	$\sum = 85$			
	Mean	**5.0**		
	Standard deviation	**9.7**		
	SE of the mean	**1.0**		

Table 10:
Pre-formed ear-plugs: differences in the means of the sound attenuation (between laboratory and plant) for the five frequencies studied

	Frequency in Hz				
	250	**500**	**1,000**	**2,000**	**4,000**
E-A-R UltraFit					
Mean	8.4	8.7	3.1	1.1	5.0
Standard deviation	8.1	9.1	9.7	9.1	10.1
Moldex Rockets Cord					
Mean	7.9	9.3	1.6	2.0	1.4
Standard deviation	8.8	11.2	10.4	11.2	12.1
Averaged over all products					
Mean	8.3	8.8	2.7	1.3	4.1
Standard deviation	8.3	9.8	9.9	9.8	10.9
SE of the mean	0.9	1.1	1.1	1.1	1.2

Table 11:
Headband ear-plugs: deviation from the sound attenuation measured in the laboratory, averaged over the frequencies

Product name	**Number of data records**	**Averaged difference in the means**	**SD of the random sample**	**Difference in the APV**
Bilsom PerCap	30	0.4	7.7	4.9
E-A-R Flexicap (under-the-chin)	33	7.7	7.2	10.0
	∑ = 63			
	Mean	**4.5**		
	Standard deviation	**8.3**		
	SE of the mean	**1.0**		

Table 12:
Headband ear-plugs: differences in the means of the sound attenuation (between laboratory and plant) for the five frequencies studied

	Frequency in Hz				
	250	**500**	**1,000**	**2,000**	**4,000**
Bilsom PerCap					
Mean	3.5	1.8	0.8	-1.5	-2.5
Standard deviation	7.2	7.7	6.5	9.6	7.7

Table 12: Continued

	Frequency in Hz				
	250	**500**	**1,000**	**2,000**	**4,000**
E-A-R Flexicap (under-the-chin)					
Mean	9.0	8.9	5.4	8.6	6.8
Standard deviation	4.9	4.0	10.1	8.4	8.7
Averaged over all products					
Mean	7.4	7.5	2.2	4.5	1.8
Standard deviation	6.7	7.3	8.9	10.3	9.4
SE of the mean	0.8	0.9	1.1	1.3	1.2

Table 13:
Ear-muffs: deviation from the sound attenuation measured in the laboratory, averaged over the frequencies

Product name	**Number of data records**	**Averaged difference in the means**	**SD of the random sample**	**Difference in the APV**
Bilsom Viking V2	33	3.0	6.7	6.9
	$\sum = 33$			
	Mean	**3.0**		
	Standard deviation	**---**		
	SE of the mean	**---**		

Table 14:
Ear-muffs: differences in the means of the sound attenuation (between laboratory and plant) for the five frequencies studied

	Frequency in Hz				
	250	**500**	**1,000**	**2,000**	**4,000**
Bilsom Viking V2					
Mean	4.1	3.6	1.3	0.8	5.0
Standard deviation	6.5	6.7	7.0	7.8	5.4
Averaged over all products (not applicable, since only one product)					
Mean	---	---	---	---	---
Standard deviation	---	---	---	---	---
SE of the mean	---	---	---	---	---

Table 15:
Custom moulded ear-plugs: deviation from the sound attenuation measured in the laboratory, averaged over the frequencies

Product name	**Number of data records**	**Averaged difference in the means**	**SD of the random sample**	**Difference in the APV**
Sicom	60	6.7	10.4	11.6
Uvex HighFit F10	69	5.5	7.4	6.4
Sonus AS	11	8.3	10.0	13.2
	$\sum = 140$			
	Mean	**6.0**		
	Standard deviation	**9.0**		
	SE of the mean	**0.8**		

Table 16:
Custom moulded ear-plugs: differences in the means of the sound attenuation (between laboratory and plant) for the five frequencies studied

	Frequency in Hz				
	250	**500**	**1,000**	**2,000**	**4,000**
Sicom					
Mean	8.5	11.0	4.3	1.0	8.5
Standard deviation	8.7	8.6	12.6	10.8	11.5
Uvex HighFit F10					
Mean	11.2	8.7	3.6	0.6	3.4
Standard deviation	7.0	8.0	8.2	6.1	7.7
Sonus AS					
Mean	12.5	11.0	10.6	3.5	2.1
Standard deviation	6.3	9.7	13.6	12.2	10.5
Averaged over all products					
Mean	10.5	9.8	4.1	0.8	4.7
Standard deviation	7.9	8.4	10.8	8.9	10.0
SE of the mean	0.7	0.7	0.9	0.7	0.8

7.1.3 Graphical presentation of the measured values – Comparison with laboratory values

Figures 8 to 20 show the sound attenuation measured in the laboratory and in the plant/audiomobile (M = mean, SD = standard deviation) at the individual test frequencies for each product studied, broken down by hearing protector type. The sound attenuation measured in the plant was adjusted by the values shown in Tables 1 and 2 (see pages 33 and 34).

a) Ear-plugs which must be formed prior to use (formable ear-plugs)

Figure 8:
Sound-attenuation values for "Moldex Spark Plugs" ear-plugs measured in the laboratory against those measured in the plant/audiomobile (88 data records)

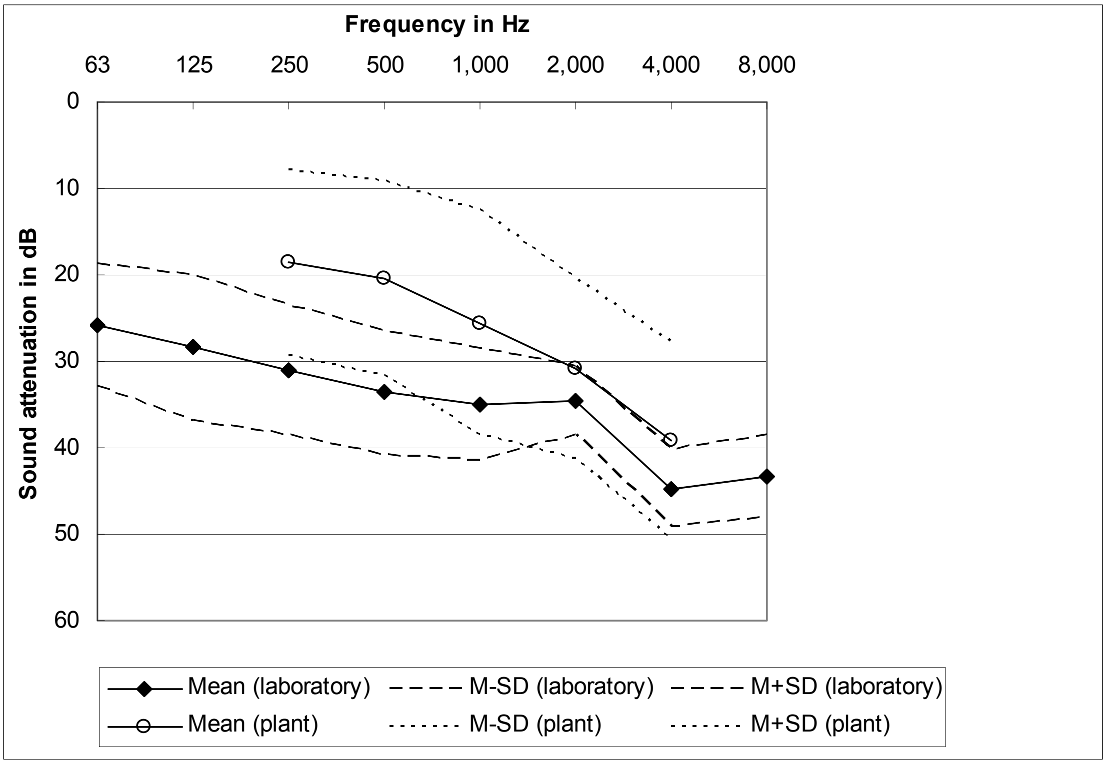


Figure 9:
Sound-attenuation values for "E-A-R Classic II" ear-plugs measured in the laboratory against those measured in the plant/audiomobile (74 data records)

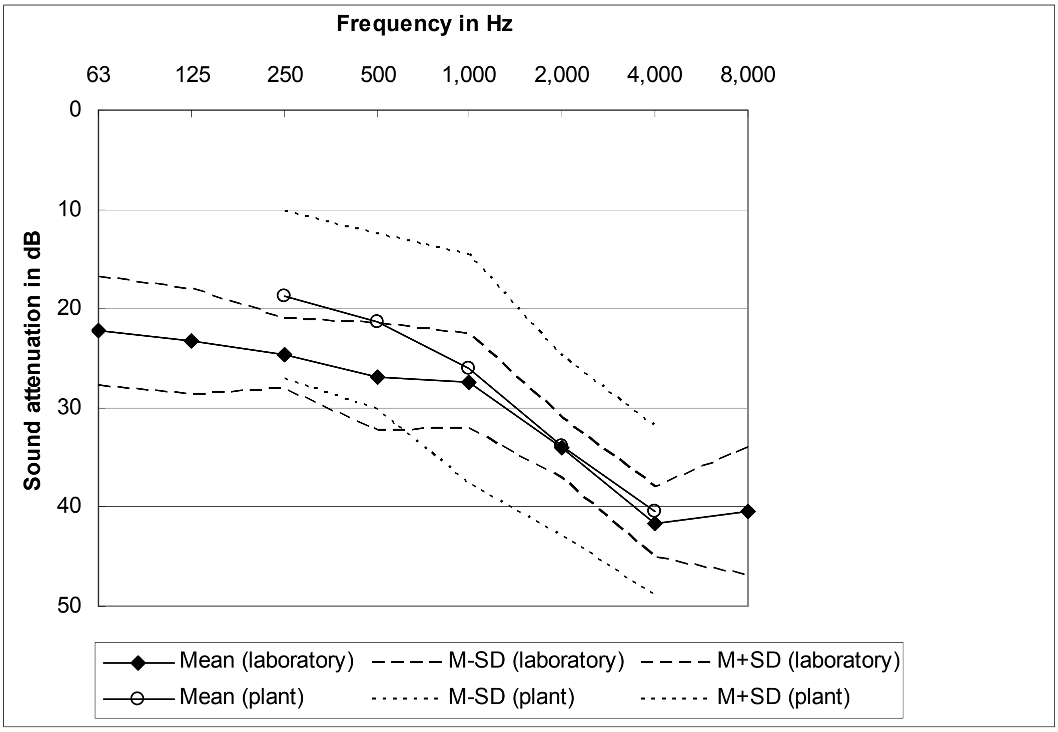


Figure 10:
Sound-attenuation values for "Howard Leight MaxLite" ear-plugs measured in the laboratory against those measured in the plant/audiomobile (37 data records)

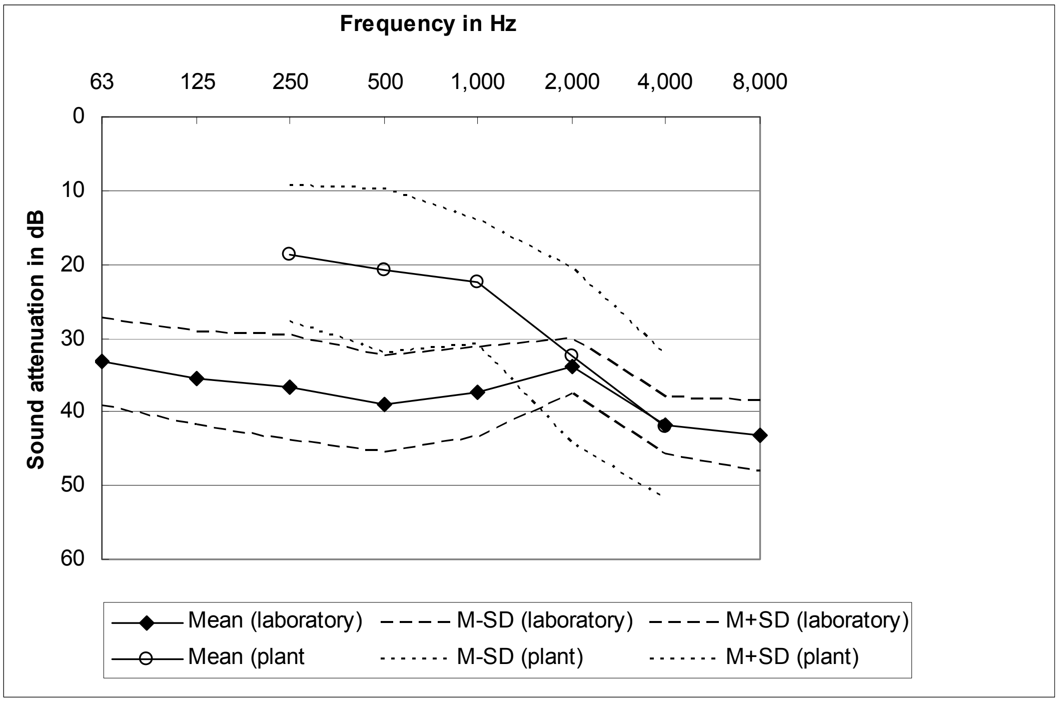


Figure 11:
Sound-attenuation values for "Bilsom 303" ear-plugs measured in the laboratory against those measured in the plant/audiomobile (38 data records)

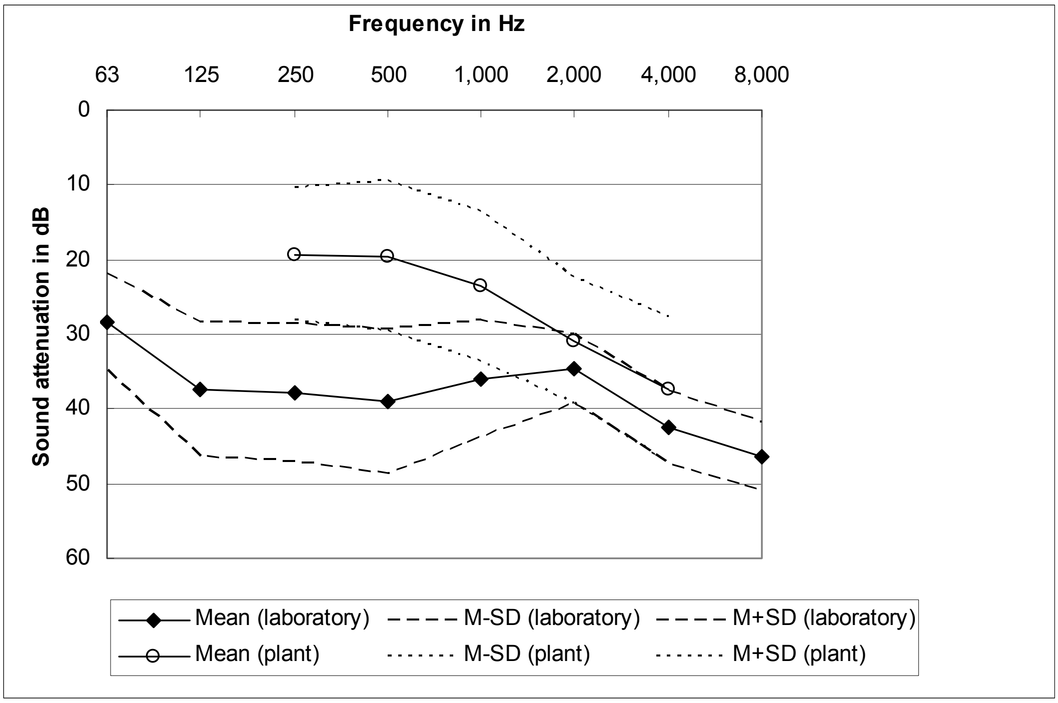
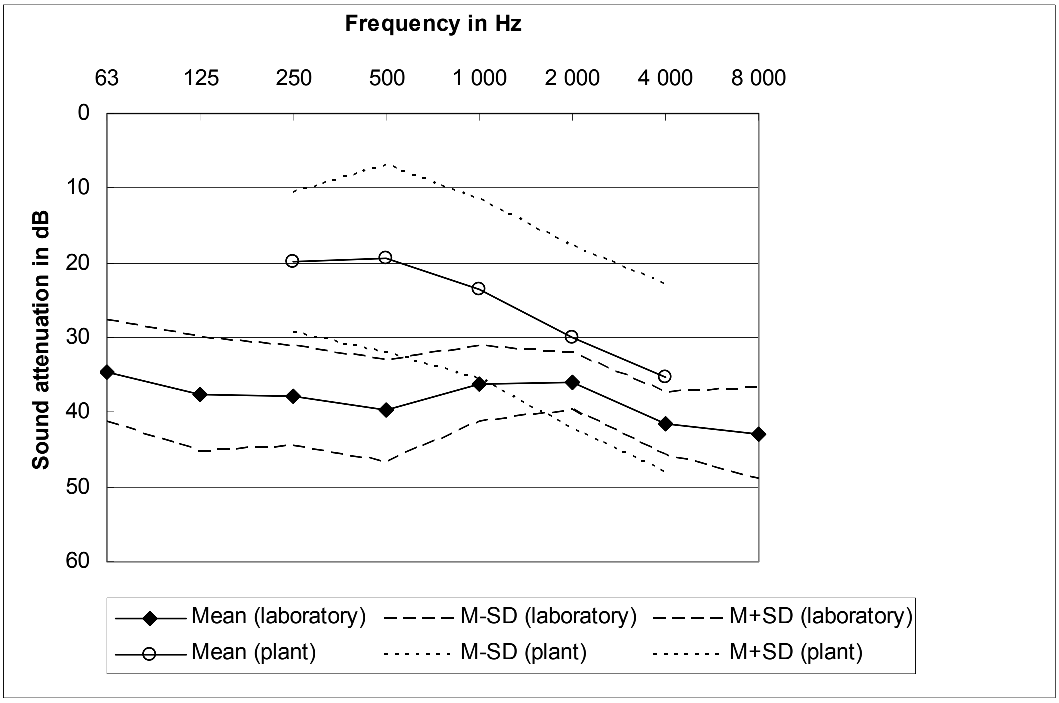


Figure 12:
Sound-attenuation values for "Howard Leight MultiMax MM-1" ear-plugs measured in the laboratory against those measured in the plant/audiomobile (25 data records)



b) Pre-formed ear-plugs

Figure 13:
Sound-attenuation values for "E-A-R Ultrafit" ear-plugs measured in the laboratory against those measured in the plant/audiomobile (58 data records)

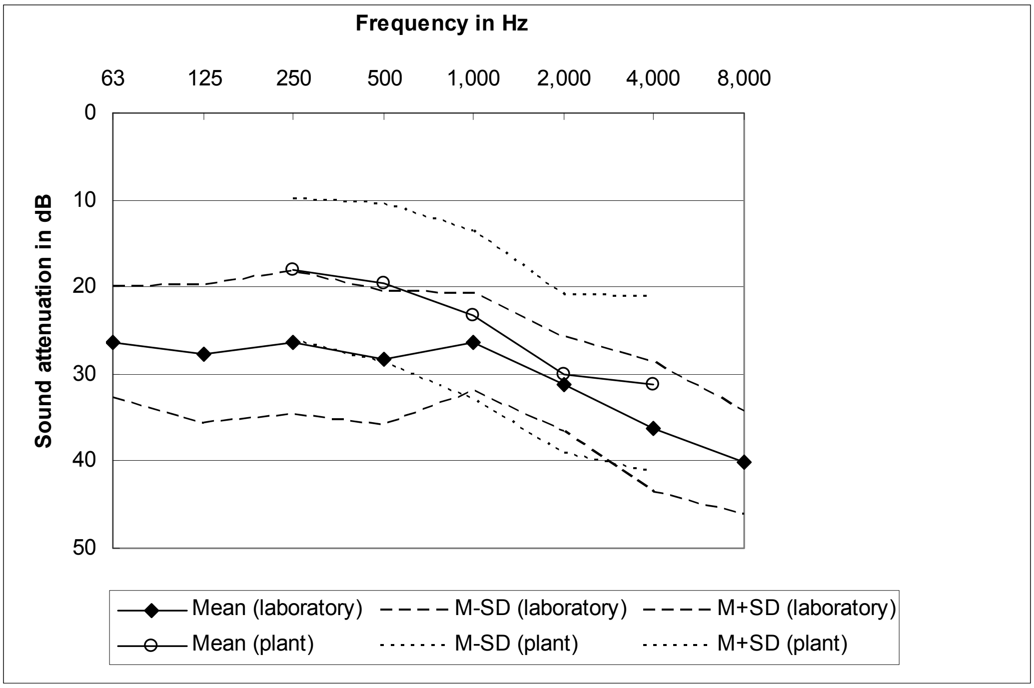
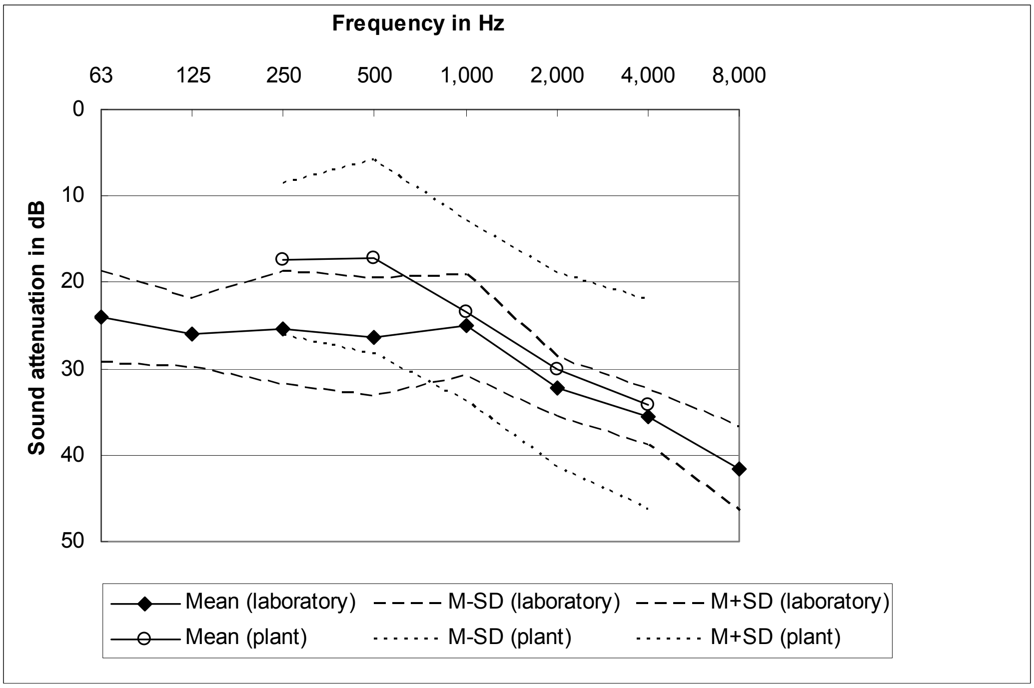


Figure 14:
Sound-attenuation values for "Moldex Rockets Cord" ear-plugs measured in the laboratory against those measured in the plant/audiomobile (27 data records)



c) Headband ear-plugs

Figure 15:
Sound-attenuation values for "Bilsom PerCap" headband ear-plugs measured in the laboratory against those measured in the plant/audiomobile (30 data records)

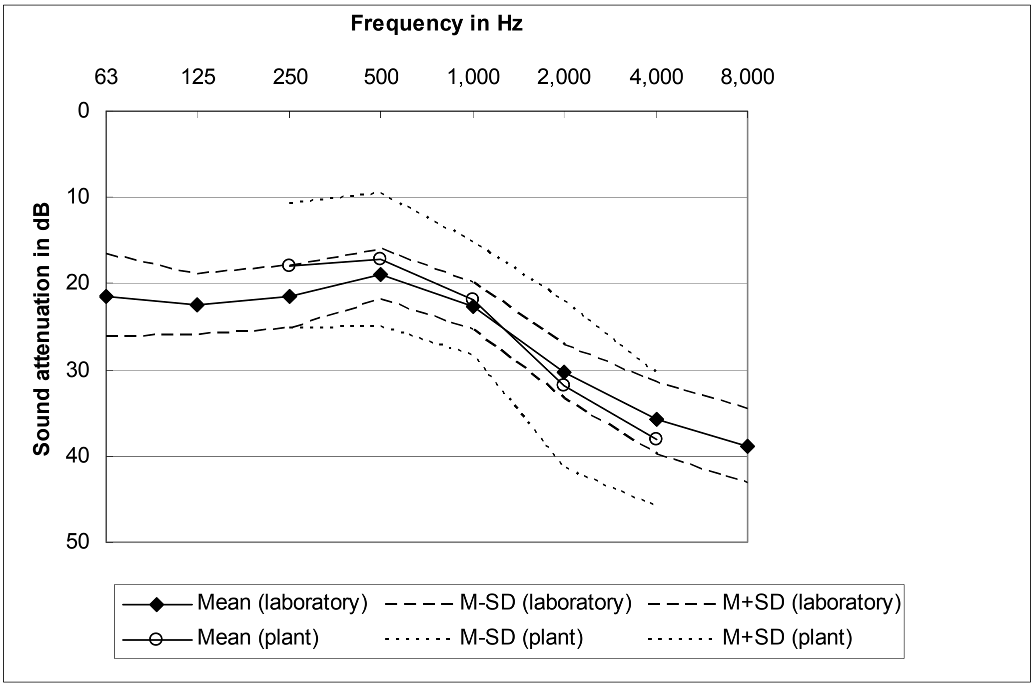
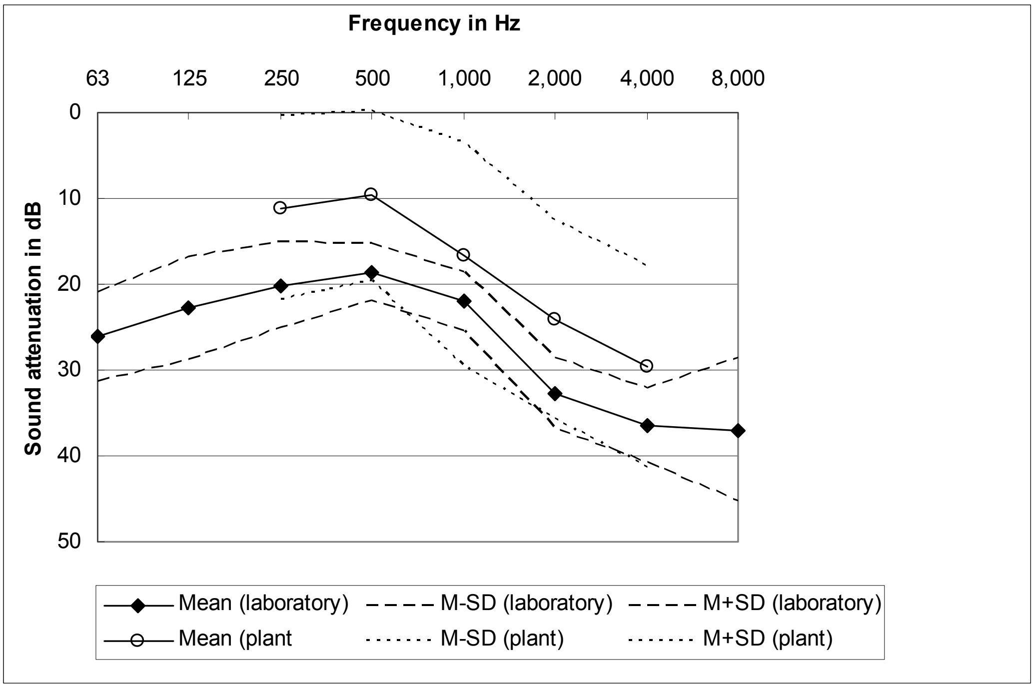
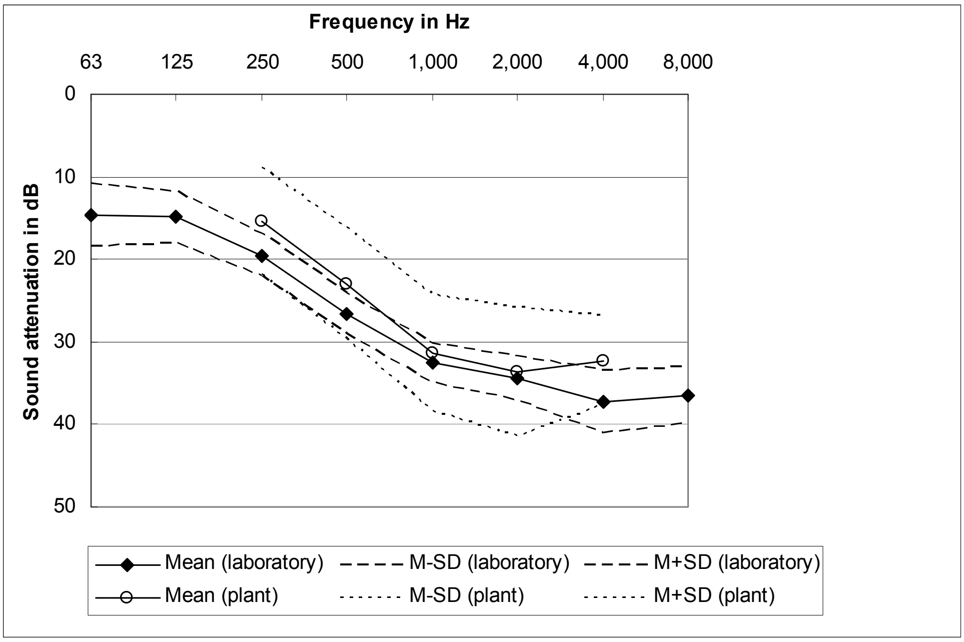


Figure 16:
Sound-attenuation values for "E-A-R Flexicap" headband ear-plugs measured in the laboratory against those measured in the plant/audiomobile (33 data records)



d) Ear-muffs

Figure 17:
Sound-attenuation values for "Bilsom Viking V2" ear-muffs measured in the laboratory against those measured in the plant/audiomobile (33 data records)



e) Custom moulded ear-plugs

Figure 18:
Sound-attenuation values for "Sicom" custom moulded ear-plugs measured in the laboratory against those measured in the plant/audiomobile (60 data records)

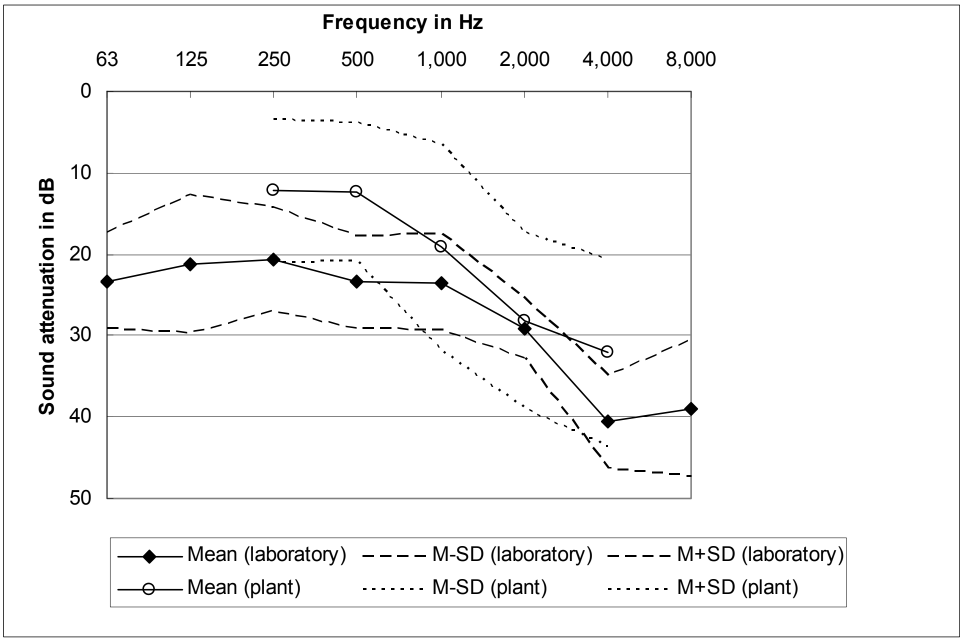


Figure 19:
Sound-attenuation values for "Uvex HighFit F10" custom moulded ear-plugs measured in the laboratory against those measured in the plant/audiomobile (69 data records)

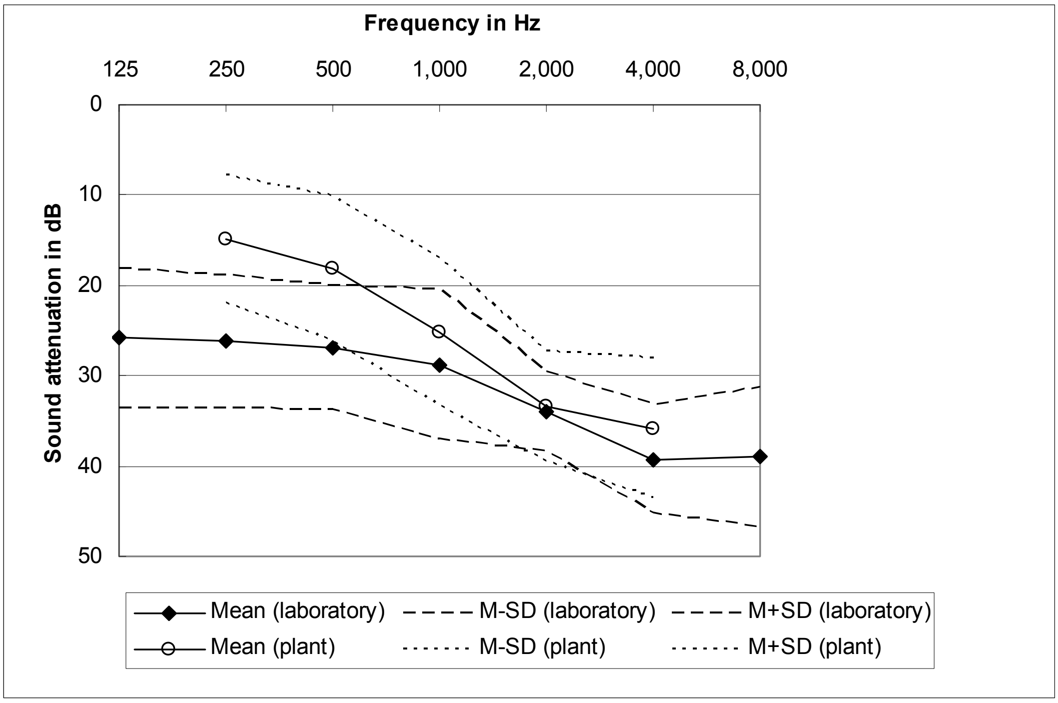
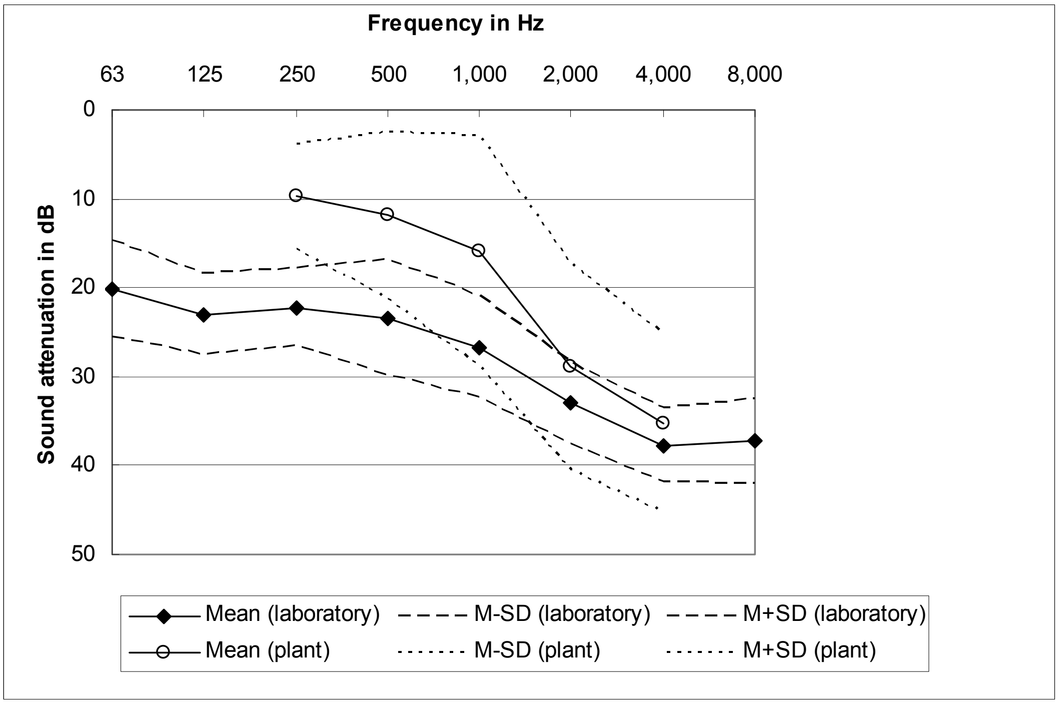


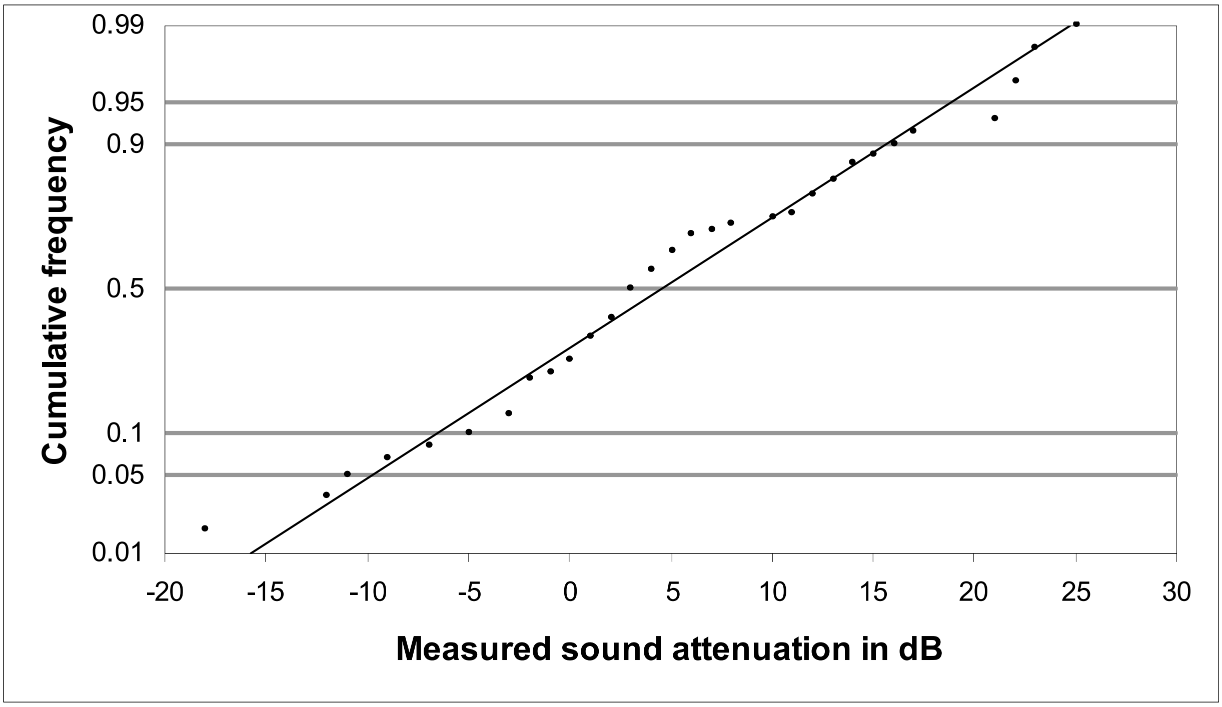
Figure 20:
Sound-attenuation values for "Sonus" custom moulded ear-plugs measured in the laboratory against those measured in the plant/audiomobile (11 data records)



7.1.4 Results of the test for normal distribution

The two methods described in Section 6.5 for testing for normal distribution were applied to selected data records serving as examples. Figure 21 shows by way of example the sound attenuation measured in the audiomobile at the frequency of 250 Hz for a custom moulded ear-plug for which 60 discrete values are plotted on a probability paper. The straight line corresponds to a normal distribution with the mean (4.5 dB) and the standard deviation (8.7 dB) of the random sample. Taken as a whole, the measured values follow the straight line; deviations can however be observed in some areas.

Figure 21:
Data record of a custom moulded ear-plug, with the cumulative frequency plotted on a probability paper, test frequency: 250 Hz, mean of the random sample: 4.5 dB, standard deviation: 8.7 dB



Statistical processing with the SPSS program yields the same result: the significance for the Kolmogorov-Smirnov test is 0.325, i.e. it cannot be excluded significantly that the data are normally distributed. A high value close to 1 would equate to data exhibiting virtually perfect normal distribution; only at values below 5% (confidence level) may it be assumed that the data are subject to a different distribution. A further method of visualizing the data and their distribution is by means of a histogram with the associated normal distribution (Gaussian bell curve, see Figure 22). In this presentation, too, slight differences from a normal distribution are evident.

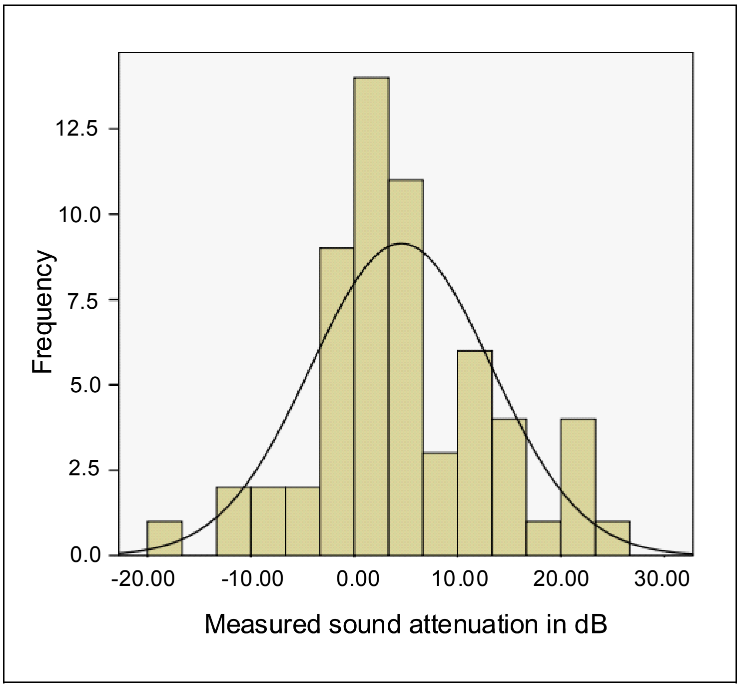
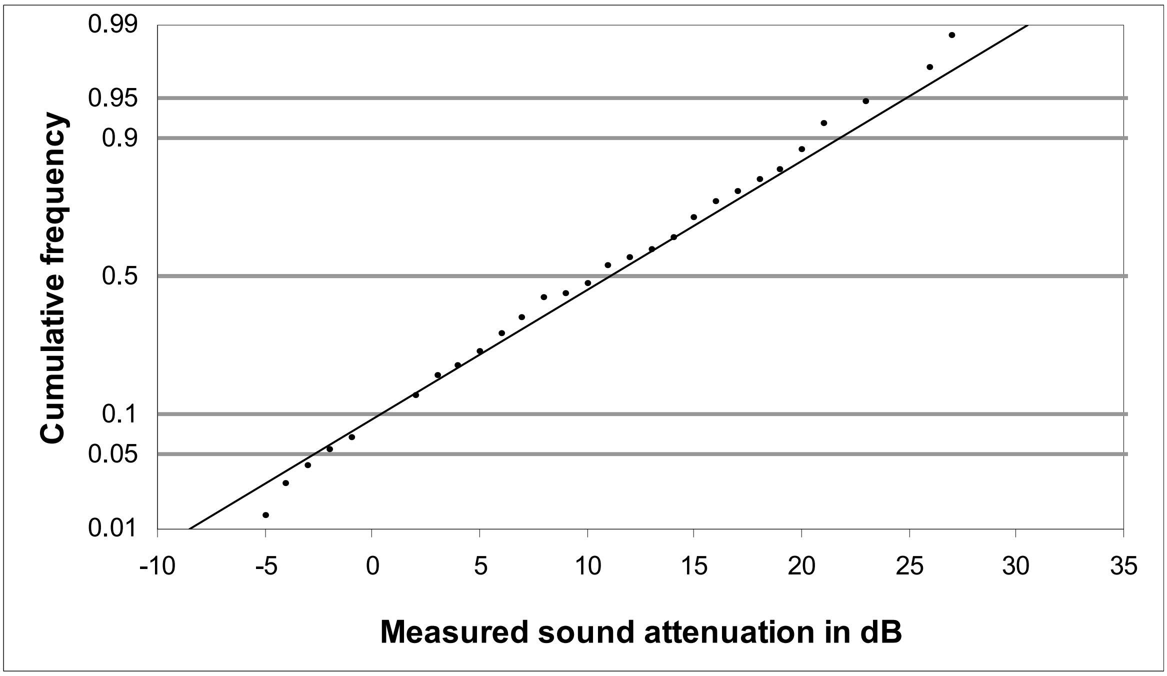


Figure 22:
Histogram of the data record from Figure 21, with normal distribution calculated from the size of the random samples

The second example is the data record of a foam ear-plug with 74 values. Figure 23 shows the plotting on a probability paper. Only minor deviations from the reference straight line are evident in this case. Accordingly, the Kolmogorov-Smirnov test yields a high significance, of 0.887. The histogram (Figure 24) also shows the close correspondence with the normal distribution.

The interpretation of the measurement results by means of the methods described here thus confirms the assumption that the data are normally distributed. The calculations for the field derating values (Section 7.1.3) and the t-test (Section 7.1.5) may therefore be considered safe.

Figure 23:
Data record of a foam ear-plug, with the cumulative frequency plotted on a probability paper, test frequency: 250 Hz, mean of the random sample: 11.0 dB, standard deviation: 8.4 dB



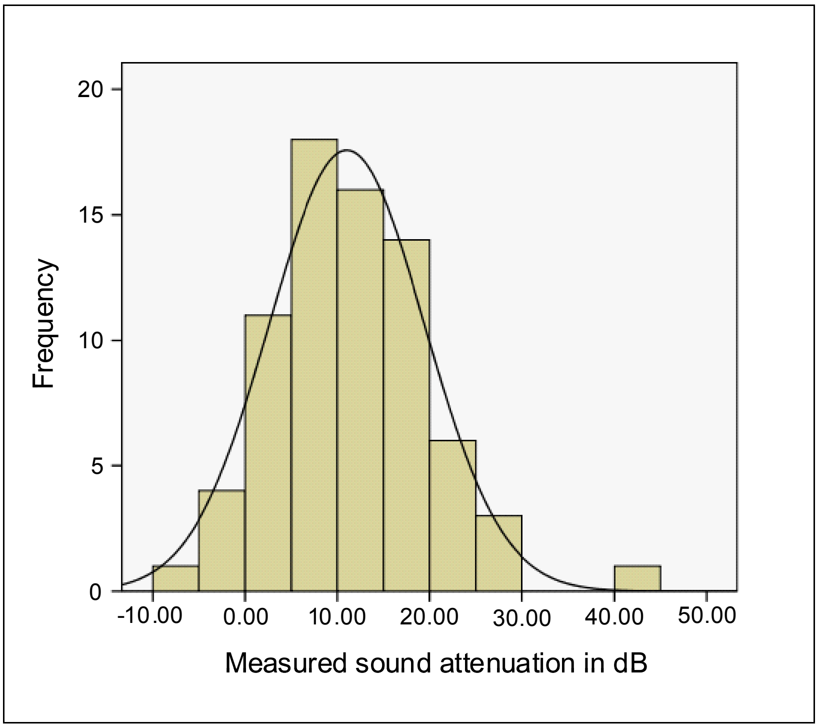


Figure 24:
Histogram of the data record from Figure 23, with normal distribution calculated from the size of the random samples

7.1.5 Results of the t-test

The t-test was used to check whether the sound-attenuation values measured in the audiomobile actually differ significantly from those measured in the laboratory. For this purpose, the data measured in the audiomobile were compared with the corresponding laboratory value for each frequency after being reduced by the relevant corrective value for effects caused by the sound field (see Section 6.3). The behaviour illustrated in the figures in Section 7.1.3 was confirmed.

13 data records each comprising five test frequencies yield a total of 65 values. For 46 of these values, the results measured in the audiomobile are substantially lower than the laboratory results, i.e. the means are different at the 5% significance level. For 18 values, no clear conclusion is possible: these audiomobile values are only marginally below (n = 16) or above the corresponding laboratory values. These sound-attenuation values are therefore comparable in size. One value however lies with high significance above that measured in the laboratory; this hearing protector thus functions better at the test frequency than in the laboratory. Since the result is significant, a measurement error cannot be assumed. However, no explanation can be found for this discrete result.

If the behaviour of the significances as a function of the frequency is considered, it is notable that at the low frequencies, the differences between the laboratory and audiomobile measurements are clear for almost all hearing protectors; at the high frequencies (particularly 2 kHz), the behaviour is no longer as clear.

7.1.6 General discussion

Various conclusions can be drawn from the measurement results and figures.

The figures in Section 7.1.3 show that the greatest difference in sound attenuation between laboratory and the field occurs at low frequencies of up to 1 kHz. This is as expected: leakage such as that caused by improper fitting or insertion has a particularly strong effect at low frequencies. The effect should be even stronger for frequencies below 250 Hz; frequencies below this level could not be measured in the test arrangement, however. In addition, measured values for 8 kHz are not available, with the result that correction of the attenuation values according to frequency is not possible.

If the differences between sound attenuation in the laboratory and the field – averaged over the five frequencies and all products studied – is compared as in

Table 6 (see page 46), differences between the individual hearing protector types are evident. The greatest deviation, of almost 8 dB, is observed for ear-plugs which must be formed prior to use (see also Section 7.3, page 65).

Since a number of products were studied for each hearing protector type, it was also possible for them to be compared with each other in terms of their respective differences to the sound attenuation measured in the laboratory. Products were observed both with very similar results, and with substantially different results. These observations are discussed in more detail in Section 7.2.

7.2 Comparability of different hearing protectors of the same type

Since the corrective values for the sound attenuation determined in the course of this study are to be applicable for all hearing protectors, an attempt was made to study as many different products as possible in the field studies. By averaging of the values for several products of one type, a meaningful value was to be arrived at under ideal circumstances. For some types, only two products with an adequate random sample size are unfortunately available; it was however not possible to obtain further data during the course of the project.

This section discusses the homogeneity of the results for the individual hearing protector types, i.e. the extent to which the result is dependent upon the product concerned.

Formable ear-plugs constitute the largest group in this study, with five products tested. Tables 7 and 8 provide an overview of the deviations from the sound attenuation measured in the laboratory. As anticipated, these values are relatively high, since the products consisting of foam require particularly careful insertion (rolling prior to use, deep insertion, sufficiently long location) in order for the desired protective action to be achieved. For four of the five ear-plugs, deviations of approximately 9 to 12 dB from the laboratory values are observed; for one product (E-A-R Classic II), however, the value was only 2.8 dB. A possible explanation is the material and thus also the surface property of this ear-plug. In contrast to the other products studied, it is manufactured from polyvinyl chloride (PVC) rather than polyurethane (PU), making it relatively rough and possibly less likely to slip out of the ear canal as easily. Repeat measurement on subsequently purchased samples of E-A-R Classic II in the BGIA's laboratory under type-examination conditions yielded higher sound-attenuation values, resulting in a greater difference between the values measured in the laboratory and those measured in the audiomobile. This was however only a random sample measurement and not the full procedure to DIN ISO 4869-1. Altogether, the five products in this category yield a weighted mean of 7.8 dB; the influence of the data from the repeat measurement upon this value would be only minor.

In the next group, that of re-usable pre-formed ear-plugs, two products with an adequate random sample size were studied. The sound-attenuation values for these two products, both the laboratory values and those from the audiomobile, are close, resulting in very similar corrective values for the two ear-plug products (5.2 dB and 4.4 dB).

Two products in the category of headband ear-plugs were also considered for interpretation. They exhibit similar laboratory values; the results from the audiomobile differed more strongly, however. The deviation averaged over the frequencies was 0.4 dB for the Bilsom PerCap and 7.7 dB for the E-A-R Flexicap (headband worn under the chin). The only notable observation is that the correction values for the sound field in the audiomobile were obtained by comparative measurement with the PerCap (see Section 6.3). It is not anticipated that the correction values have been determined incorrectly, however, since the same test procedure applied to ear-muffs yielded a consistent pattern for the different measurement situations. The weighted mean from the two data records is 4.5 dB.

For the ear-muff group, data were obtained for six products; only two random samples were of adequate size, however. It proved difficult to find plants in which ear-muffs were used in larger numbers. The results for the two products were highly heterogeneous. The hearing protector by means of which the correction values for the sound field were determined in the audiomobile (see Section 6.3) exhibits a difference from the laboratory value of 3.0 dB even after correction. For the other product, however, a negative deviation of -2.2 dB was obtained, i.e. the attenuation determined in the audiomobile (including correction) is superior to that measured in the type examination. If it is assumed that the sound attenuation measured in the laboratory is the best possible and that the difference from the value measured in the audiomobile therefore cannot be lower than zero, the value determined in this case provides an indication of the uncertainty of the method. The deviations for the frequencies of 1 and 2 kHz are however relatively large, and according to the t-test are significant. The product designation was therefore checked again in the plant, and the sound attenuation measured again in the laboratory on purchased samples. Since this yielded no deviations from the laboratory values stated by the manufacturer, the cause of the strong discrepancy between audiomobile and laboratory values is not clear. This data record was not therefore used for interpretation. Comparison with the results from the first study [4] shows that it also yielded a substantially reduced sound attenuation for ear-muffs in the field (mean: 4.5 dB). The value now determined of 3.0 dB is therefore in the same region.

Five data records are available for custom moulded ear-plugs; only three of them could be interpreted, however, since for one product it could not be determined which filter had been used, and a second was in use with a total of six different filters, with the result that only a small number of data records were available for each filter. Two random samples, one with 60 measurements and the other with 69, exhibit mean deviations from the sound attenuation measured in the laboratory of 6.7 dB and 5.5 dB, respectively. The third data record, with only eleven measurements, yields a difference of 8.3 dB. Owing to its small size, however, its influence during averaging is minor, resulting in a mean for this hearing protector type of 6.0 dB. In all three cases, the fit of the products was not examined at delivery (or shortly afterwards) by a skilled person and a suitable measurement method. It may be assumed that such a functional check would on average lead to superior sound attenuation (see Section 7.4, page 66).

7.3 Influence of the hearing protector type upon sound attenuation in the field

Table 6 (see page 46) reveals substantial differences between the hearing protector types in the differences in their sound attenuation between the laboratory and the field. The values confirm those from the BGIA's first study [4] on this subject.

The hearing protectors with the greatest deviation between the values obtained in the laboratory and in the plants are formable ear-plugs, with a value of 7.8 dB; individual products exhibited differences of over 10 dB. The other types of ear-plugs can apparently be inserted better in field use than those manufactured from foam, since pre-formed ear-plugs and headband ear-plugs exhibit differences of only 5.0 dB and 4.5 dB respectively.

The first study did not differentiate between different types of ear-plugs; it resulted in a derating value of 9 dB. The new results show that the situation has not changed for foam ear-plugs; these products are evidently those most frequently associated with user error. The other types of ear-plugs (pre-formed and banded) do not need to be formed prior to insertion into the ear canal, nor does the user have to locate them there for a period. This explains the lower deviations from the sound attenuation measured in the laboratory. At approximately 5 dB in each case, however, these values are not negligible: users must also be instructed to insert these ear-plugs carefully.

Ear-muffs also yielded significant deviations between the sound attenuation measured in the laboratory and in practice. Since only one product was studied for which the data could be interpreted, however, quantitative conclusions are not possible. The derating value of 5 dB from the first study is consistent with the new data.

Custom moulded ear-plugs yield a deviation of 6.0 dB from the sound attenuation measured in the laboratory, somewhat higher than the values for pre-formed ear-plugs. Since at the time of the first study in 1989, custom moulded ear-plugs were not widely used in Germany, comparative data are not available. The next section addresses the particular aspects relating to this product group (i.e. how frequently sealing is checked?).

7.4 The special case of custom moulded ear-plugs: regular functional checks required

Custom moulded ear-plugs differ from other hearing protector types in one important respect: they are manufactured individually for the ear canal of their user. From an impression of the ear canal, an ear-plug is manufactured which fits only in this particular ear canal, but is intended to seal it fully. In some custom moulded ear-plug products, the sound attenuation is determined by the attenuating action of the integral filter, and can therefore be selected within certain limits according to the noise exposure level.

Whether a custom moulded ear-plug is fitted tightly is therefore normally dependent not upon the care taken during its insertion, but upon the proper fit. During manufacture, errors may occur in a significant number of cases [12] which result in the ear canal not being completely closed. Besides inadequate manufacturing tolerances, problems may arise during taking of the impression, such as air inclusions in the impression mass, injection of the mass at excessive pressure, or speaking, chewing, facial expressions and swallowing by the test subject whilst the mass is curing. In addition, a custom moulded ear-plug which fits tightly after manufacture may fail to seal over time, since the geometry of the ear canal may change over a period of several years. Since the resulting reduction in the sound attenuation is progressive, it usually passes unnoticed.

In order to prevent employees from wearing custom moulded ear-plugs which do not attain the desired sound attenuation, their sealing must be tested [6]. Various methods exist for this purpose. None of the products examined in this study was subjected to functional checks. It is not therefore possible for the two types of custom moulded ear-plugs to be compared.

The correction value of 6.0 dB which was determined applies to products which are not checked regularly. It is therefore somewhat higher than that for pre-formed ear-plugs which shows that the reliability of such custom moulded ear-plugs is at best equal to that for ear-plugs which are not adapted to the individual user. Where their function is checked regularly, a lower deviation from the sound attenuation measured in the laboratory may be anticipated.

7.5 Consequences for the selection of hearing protectors

In accordance with the German Noise and Vibration OSH Ordinance [1], the maximum permissible exposure values may not be exceeded at the ear of the employee. The attenuating effect of hearing protectors is taken into consideration for this purpose. In order for allowance to be made for the reduced sound attenuation in the field, the "PPE equipment" expert committee specified the following derating values [13] following entry into force of the Ordinance. These values are based upon the first study by the BGIA [4]:

- 9 dB for ear-plugs,
- 5 dB for ear-muffs and
- 3 dB for custom moulded ear-plugs subject to regular functional checks.

At the same time, the expert committee launched the present study in order for the values to be updated.

Based upon the new data that have been obtained and with reference to the former values, the following, more differentiated derating values are proposed:

- 9 dB for formable ear-plugs,
- 5 dB for pre-formed ear-plugs,
- 5 dB for headband ear-plugs,
- 5 dB for ear-muffs,
- 3 dB for custom moulded ear-plugs subject to regular functional checks,
- 6 dB for custom moulded ear-plugs without functional checks,
- 9 dB for combinations of ear-muffs and ear-plugs.

These correction values take account of the fact that formable ear-plugs are often inserted less carefully than pre-formed ear-plugs.

In addition, the lower derating value for custom moulded ear-plugs which are subject to regular functional checks will result in only products for which the manufacturer offers this service being purchased.

Qualified use: The reduced sound attenuation in the field may lead to problems at certain workplaces where high sound levels occur or signals must be heard. At extreme exposure levels, such as those encountered during CO_2 blasting, hearing protectors with the highest available attenuation (and possibly double hearing protection, i.e. ear-plugs plus ear-muffs) must be used in order for the maximum permissible exposure value to be observed. At the usual leakage levels, which are reflected in the field derating values, the resulting attenuation may no longer be sufficient under certain circumstances. In such exceptional cases, suitable instruction (see Section 7.6) must be assured in order for the sound attenuation level measured in the laboratory actually to be attained in the plant [14]. Where instruction is provided, the "PPE" expert committee [15] has specified that the deratings need not then be applied.

A similar problem exists for the hearing of signals. These include speech, sounds from the work process which impart information, warning signals in general, and also particular cases such as permanent track layers or drivers of vehicles on the public highway. For these special cases, additional arrangements exist for the licensing and use of hearing protectors. The suitability of a hearing protector for the perception of signals is determined in the first instance by calculation based upon the sound-attenuation values measured in the laboratory. Should poor fitting substantially impair the attenuation, it can no longer be assumed that this property is retained. Hearing protectors with an attenuation curve which is as independent as possible of the frequency are generally well-suited to the perception of signals. In contrast, products with low attenuation values at low frequencies lead to signal components even at higher frequencies being masked, owing to psychoacoustic effects. Since incorrect fitting or insertion of hearing protection facilitates the passage of low frequencies in particular (refer to the graphs in Section 7.1.3), these masking effects may also occur for products which are attested by the type examination with a flat attenuation curve. Employees for whom the correct hearing of signals is very important should therefore be instructed in the use of their hearing protector, in order to avoid the need for application of the field derating values. The ability to perceive signals whilst wearing a hearing protector can be checked on site by a hearing test. For some workplaces, this test is mandatory.

Implementation of the results: The "PPE" expert committee has already implemented the correction values derived from this study in the form of field derating values, and incorporated them into its publications. These informative publications include codes of practice which are available on the committee's website [15], and also and in particular publications such as BGR 194 [5], BGI 5024 [16] and BGI 8621 [17].

They are geared to specific target groups, such as labour inspectors, OSH professionals, small and medium-sized businesses, or the employees themselves.

In addition, the field derating values are taken into account in the BGIA software for the selection of hearing protectors [18] which can be downloaded from the BGIA's website. Particularly worth mentioning is a program for orchestra musicians [19] which supports the user in determination of an exposure level and selection of a suitable hearing protector.

A range of methods are used in different countries in order to take account of the reduced sound attenuation in practice (see Chapter 3, page 19). The revision of DIN EN 458 is also to consider the need for derating values; the different methods could be compiled in an informative annex to this standard.

7.6 Consequences for instruction in the use of hearing protection

The results of this study show that on average, the sound attenuation measured in the laboratory is not actually attained in practice for any of the hearing protector types. This reduction in the sound attenuation is due in many cases to incorrect use of the products (Chapter 2, page 15). For this reason, particular importance should be attached to proper use of hearing protection during instruction provided to employees in the plants. The known sources of error should be pointed out, and proper behaviour demonstrated. The most effective measure however is practice, during which the employees fit or insert their hearing protectors under supervision. Earplugs which must be formed prior to use, in particular, require regular training before the individual steps (rolling, inserting and locating) are mastered.

Qualified use: As described in Section 7.5, attainment of the laboratory sound attenuation level is a requirement at some workplaces. The field derating values can be ignored if special instruction ensures that the sound-attenuation values measured in the laboratory are attained [14]. The "PPE" expert committee has specified [5; 15] that exercises must be conducted at least four times a year during which correct use of the hearing protection is also checked.

Checking of the protective action: In order to ascertain whether a hearing protection is being used correctly, commercially available test systems may be useful for measurement of the individual sound attenuation of a hearing protector (usually ear-plugs) [20]. For this purpose, manufacturers of hearing protection have developed a variety of measurement methods. These include measurement of the sound-pressure level by means of a miniature microphone in the ear canal under the hearing protector; measurement of the hearing threshold with and without hearing protection, similar to the type examination; or comparison of the loudness between the two ears, with and without hearing protector. In all of these systems, consideration must of course be given to the uncertainty of the results caused for example by the measurement uncertainty or the reproducibility of subjective methods. At present, it is not yet possible to determine absolute sound attenuation values by means of these test systems; only the comparison with reference values declared by the manufacturer concerned is meaningful. Such systems enable the effects of poorly inserted ear-plugs to be demonstrated to the user. At the same time, he or she is provided with feedback on the success of instruction and training when the sound attenuation is improved; motivation is therefore likely to increase for the instructions to be implemented carefully.

7.7 Consequences for preventive medical check-ups

The correct use of hearing protectors should also be discussed during preventive medical check-ups (refer for example to BGI 823 [21]). Employees must be conscious of the extent to which the protective action may decrease should they fail to use hearing protection properly. In order to illustrate this, the use of test systems for hearing protection (see Section 7.6) may also be advantageous here. The occupational physician may also recommend that the employer use such a system in order to instruct employees; the limitations of such equipment as described above must of course always be taken into account.

In situations involving very high exposure levels, it may be advantageous to recommend a qualified use (see page 68), since the field derating values then need no longer be applied. Should a change of hearing protector type, for example from ear-muffs to ear-plugs, be indicated for medical reasons, different field derating values may be required. In such cases, the occupational physician should inform the employer that a new risk assessment may be necessary.

Two further important issues which could lead to reduction of the sound attenuation should also be raised during check-ups: the period of wearing, and the ageing of the hearing protection. Even short periods during the working shift in which hearing protectors are not worn may reduce the effective attenuation significantly, with the result that values may arise which exceed the maximum permissible exposure value at the ear. Hearing protectors the characteristics of which have changed during use or storage may exhibit a lower sound attenuation, for example as a result of defective sealing cushions on ear-muffs or hardening of the material of ear-plugs. This subject has been examined both in the previous BGIA study [4], and in studies conducted by other institutes [22]. Visual inspections of the hearing protector during the occupational medical check-ups may enable such faults to be detected and corrected.

For employees who have already suffered hearing loss, in particular, adequate protection of the hearing is absolutely essential. In such cases, custom moulded ear-plugs are recommended. Their protective action must be checked regularly. This enables a reliable sound attenuation to be attained.

8 References

[1] Verordnung zum Schutz der Beschäftigten vor Gefährdungen durch Lärm und Vibrationen (Lärm- und Vibrations-Arbeitsschutzverordnung – LärmVibrationsArbschV) vom 6. März 2007. BGBl. I (2007), p. 261

[2] *Berger, E. H.; Franks, J. R.; Lindgren, F.*: International review of field studies of hearing protector attenuation. In: *Axlesson, A.; Borchgrevink, H.; Hamernik, R. P.; Hellstrom, P.; Henederson, D.; Salvi, R. J.* (Ed.): Scientific basis of noise-induced hearing loss. Chapter 29, S. 361-377. Thieme, New York 1996

[3] *Neitzel, R.; Seixas, N.*: The effectiveness of hearing protection among construction workers. J. Occup. Environm. Hyg. (2005) No. 2, p. 227-238

[4] *Pfeiffer, B. H.; Kuhn, H.-D.; Specht, U.; Knipfer, C.*: Schalldämmung von Gehörschützern in der betrieblichen Praxis. BIA-Report 5/89. Ed.: Berufsgenossenschaftliches Institut für Arbeitssicherheit – BIA, Sankt Augustin 1989

[5] Berufsgenossenschaftliche Regel für Sicherheit und Gesundheit bei der Arbeit: Benutzung von Gehörschutz (BGR/GUV-R 194). Ed.: Deutsche Gesetzliche Unfallversicherung, Berlin 2008. Carl Heymanns, Cologne 2008. www.arbeitssicherheit.de/arbeitssicherheit/html/modules/bgr150199/150-199/bgr194.pdf

[6] Otoplastik – ein spezieller Gehörschutz. BGIA-Info 7/2000. Ed.: Berufsgenossenschaftliches Institut für Arbeitssicherheit – BIA, Sankt Augustin 2000

[7] *Trompette, N.; Canetto, P.*: International practise about "real world" exposure beneath HPD. Ed.: Institut National de Recherche et de Sécurité (INRS), Vandoeuvre, France 2007

[8] Criteria for a recommended standard: Occupational noise exposure (Revised criteria 1998). NIOSH-Publication 98-126. Ed.: U.S. Department of Health and Human Services (NIOSH)

[9] *Gozzo, J.; Thiery, L.; Canetto, P.*: Application de la réglementation sur le bruit et usage de protecteurs individuels contre le bruit (PICB) – Recommandation de l'INRS. Fiche pratique de sécurité, ed. 133. Ed.: Institut de Recherche et de Sécurité (INRS), Vandoeuvre, France 2008. www.inrs.fr/htm/application_la_reglementation_sur_bruit_usage.html

[10] DIN ISO 4869-1: Akustik – Gehörschützer – Subjektive Methode zur Messung der Schalldämmung (10/1991). Beuth, Berlin 1991

[11] *Sachs, L.*: Angewandte Statistik – Anwendung statistischer Methoden. 9th ed. Springer, Heidelberg 1999

[12] *Weiß, R.*: Studie zur Schutzwirkung von Gehörschutz-Otoplastiken. Präventionsbericht 2/2006. Ed.: Berufsgenossenschaft Metall Süd, Mainz 2006

[13] *Sickert, P.*: Gehörschutz neu geregelt. In: *Noetel, K.-H.* (Hrsg.): Handbuch Persönliche Schutzausrüstung. 75th suppl. 11/07. ecomed, Landsberg am Lech 1979

[14] *Sickert, P.*: Verbesserte Unterweisung zur Benutzung von Gehörschutz. sicher ist sicher – Arbeitsschutz aktuell (2006) No. 6, p. 294

[15] Handlungsanleitung zur Auswahl von Gehörschutz. FA „PSA“ Information zur Lärm- und Vibrations-Arbeitsschutzverordnung vom 18. Juni 2007. Ed.: Fachausschuss Persönliche Schutzausrüstung der Deutschen Gesetzlichen Unfallversicherung, Sankt Augustin 2007.
www.hvbg.de/d/fa_psa/sach/gehoersch/hand_gehoer.pdf

[16] Berufsgenossenschaftliche Information: Gehörschutz-Informationen (BGI 5024). Ed.: Deutsche Gesetzliche Unfallversicherung, Berlin 2007. Carl Heymanns, Cologne 2007.
www.arbeitssicherheit.de/arbeitssicherheit/html/modules/bgi50005099/5000/bgi5024.pdf

[17] Berufsgenossenschaftliche Information: Gehörschutz-Kurzinformationen (BGI/GUV-I 8621). Ed.: Deutsche Gesetzliche Unfallversicherung, Berlin 2008. Carl Heymanns, Cologne 2008.
www.arbeitssicherheit.de/arbeitssicherheit/html/modules/bgi8000/8000/bgi8621.pdf

[18] Software zur Auswahl von Gehörschützern. Ed.: BGIA – Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung, Sankt Augustin.
www.dguv.de/bgia, Webcode: d4785

[19] Gehörschutz – Auswahlprogramm für Orchestermusiker. Ed.: BGIA – Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung, Sankt Augustin.
www.dguv.de/bgia, Webcode: d12882

[20] *Dantscher, S.*: Methods for the determination of individual sound attenuation of ear plugs. Lecture NAG/DAGA 2009, Rotterdam (Proceedings under preparation)

[21] Berufsgenossenschaftliche Information: Ärztliche Beratung zum Gehörschutz (BGI 823). Aktualisierte Onlinefassung Mai 2008. Ed.: Fachausschuss „Persönliche Schutzausrüstungen“ der Deutschen Gesetzlichen Unfallversicherung, Berlin 2008. Carl Heymanns, Cologne 2009.
www.arbeitssicherheit.de/arbeitssicherheit/html/modules/bgi800849/800-849/bgi823.pdf

[22] *Kotarbinska, E.*: The influence of aging on the noise attenuation of ear-muffs. Noise Health 7 (2005) No. 26, p. 39-45

Annex:

Graphical presentation of the raw data measured in the audiomobile

The following figures show the raw data as measured in the audiomobile. In contrast to the figures in Section 7.1.3, correction of the sound field as discussed in Section 6.3 is not considered here.

The presentation is based upon box-whisker plots, and contains a range of information on the distribution of the data. The figures show, for each frequency, the median as a horizontal line, the 25th and 75th percentiles as a thick vertical line, and the 5th and 95th percentiles as a thin vertical line.

Presentation in this form illustrates certain characteristics of the measured distributions, such as the (a)symmetric distribution of the data around the median, and the proportion of measured values at the edges of the distribution (for example between the 75th and 95th percentiles).

As the mean and the standard deviation are always used to describe the sound attenuation values obtained in the type examination, the same arrangement was also used for interpretation of the measured values from the audiomobile. Since the mean and the standard deviation are not entered on the diagrams in this annex, differences arise (in addition to the lack of sound-field correction) between the figures in this annex and those in Section 7.1.3.

Figure A.1:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "Moldex Spark Plugs" formable ear-plug (88 data records)

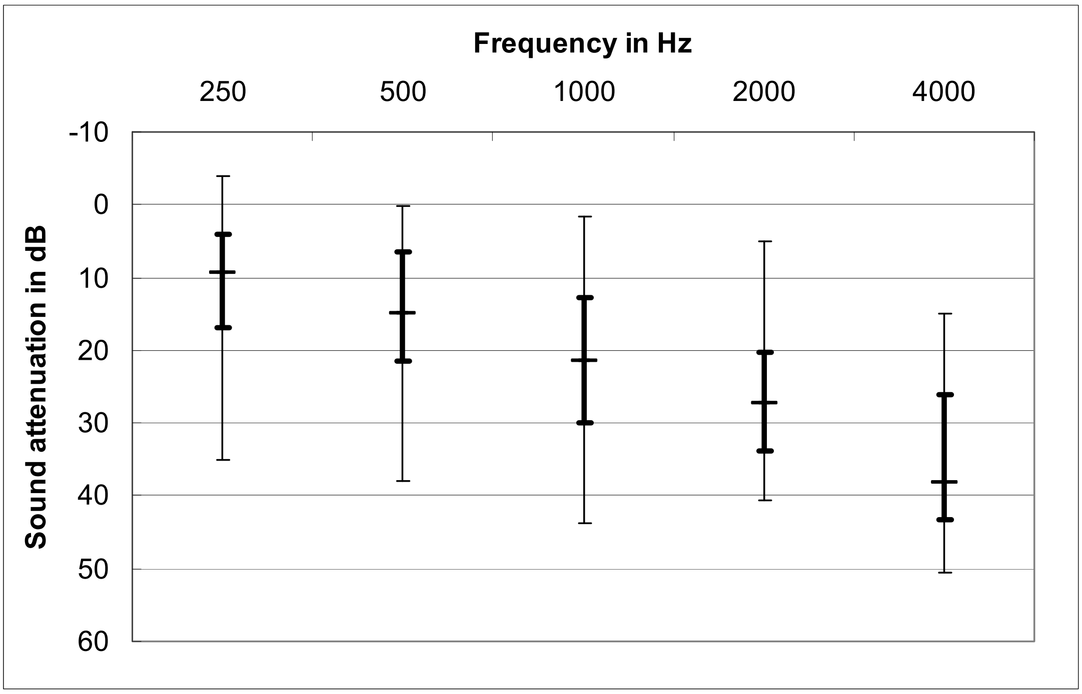


Figure A.2:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "E-A-R Classic II" formable ear-plug (74 data records)

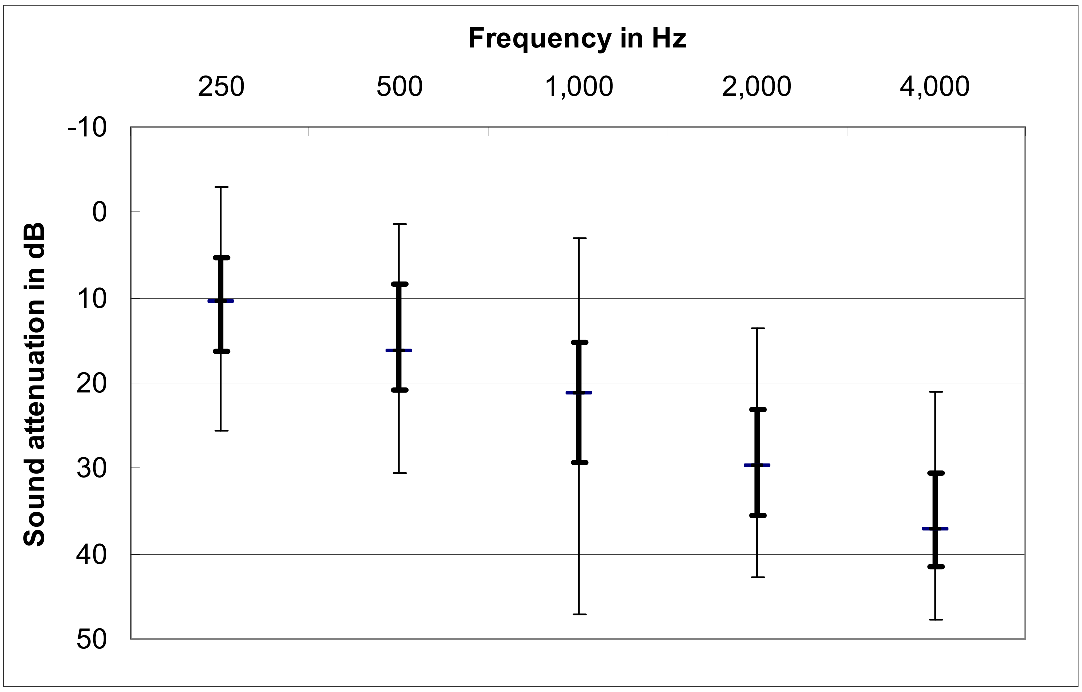


Figure A.3:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "Howard Leight MaxLite" formable ear-plug to use (37 data records)

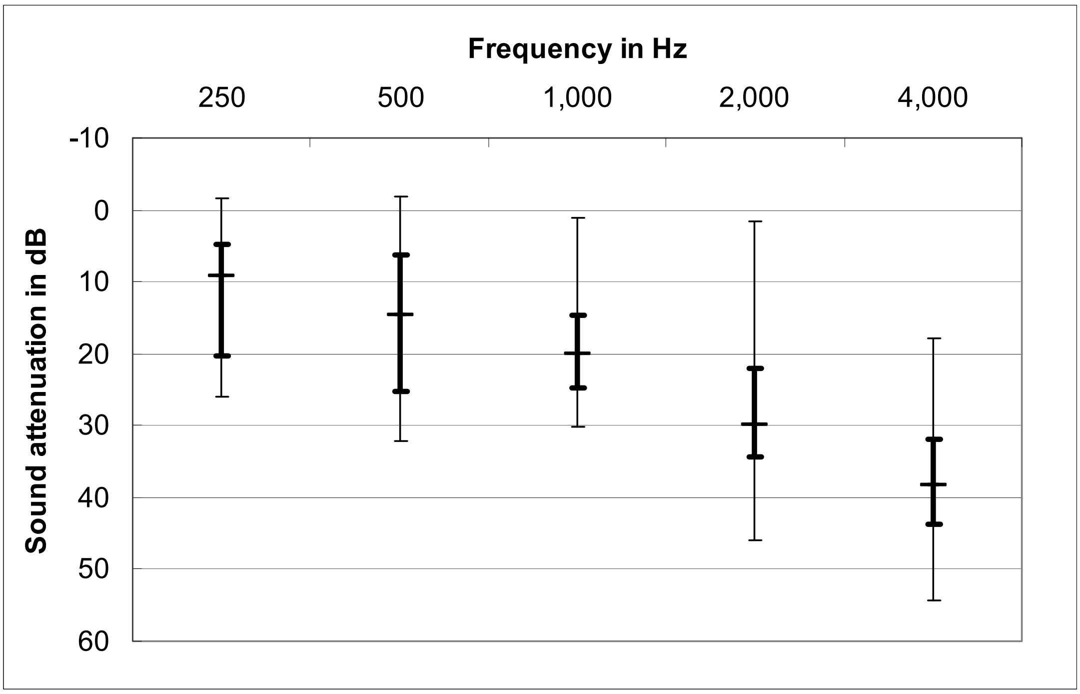


Figure A.4:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "Bilsom 303" formable ear-plug (38 data records)

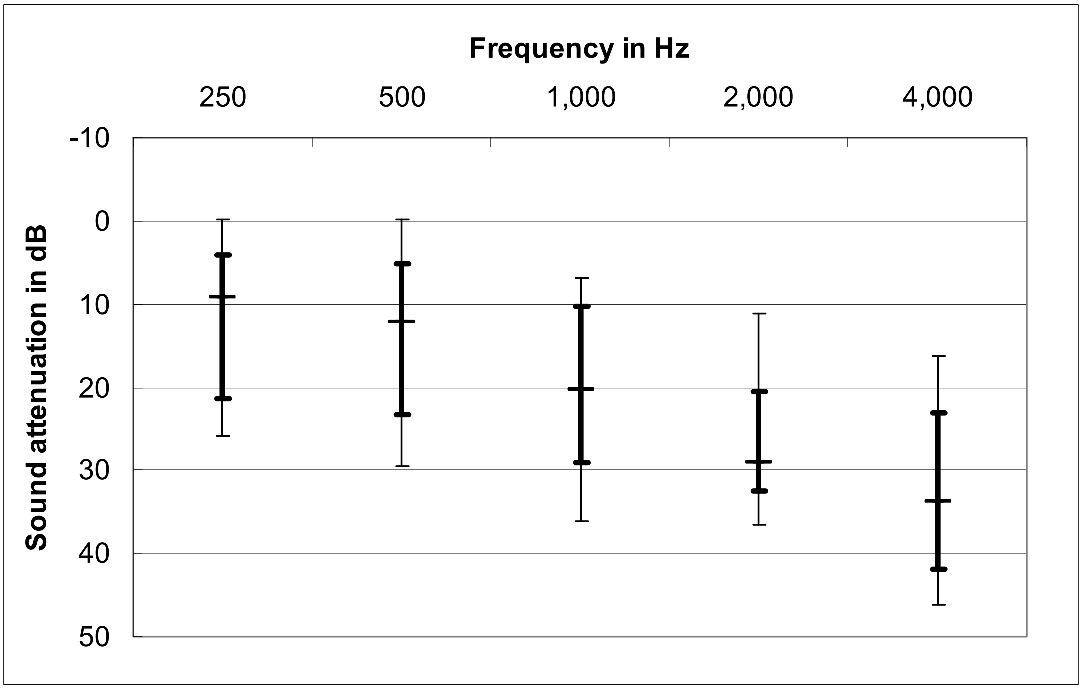


Figure A.5:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "Howard Leight MultiMax" formable ear-plug (25 data records)

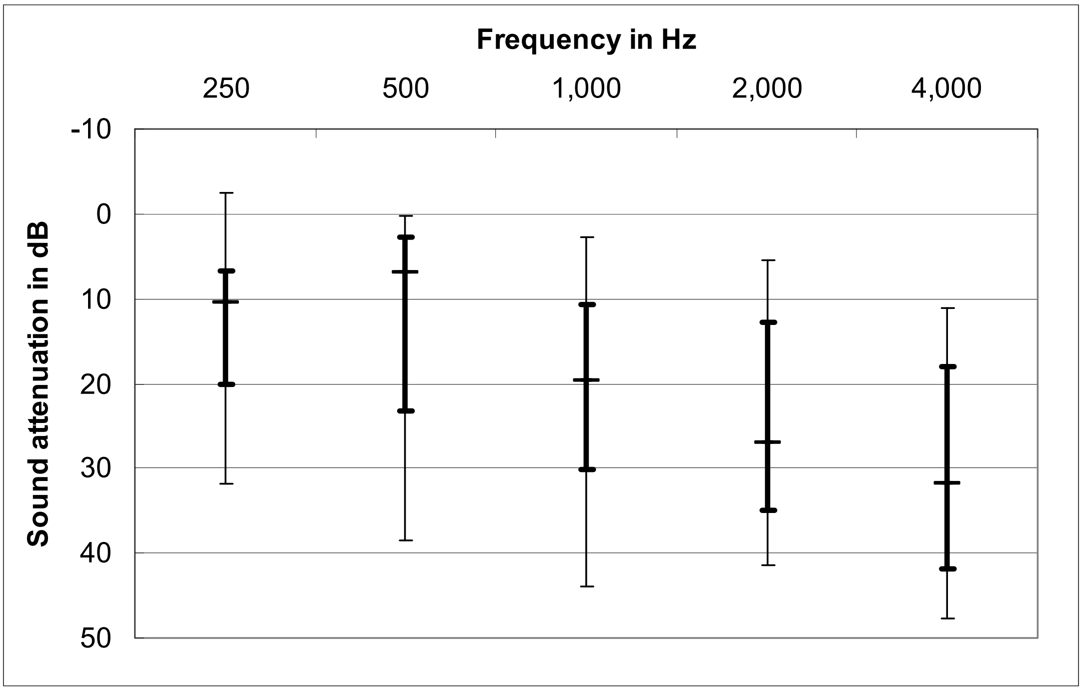


Figure A.6:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "E-A-R Ultrafit" pre-formed ear-plug (62 data records)

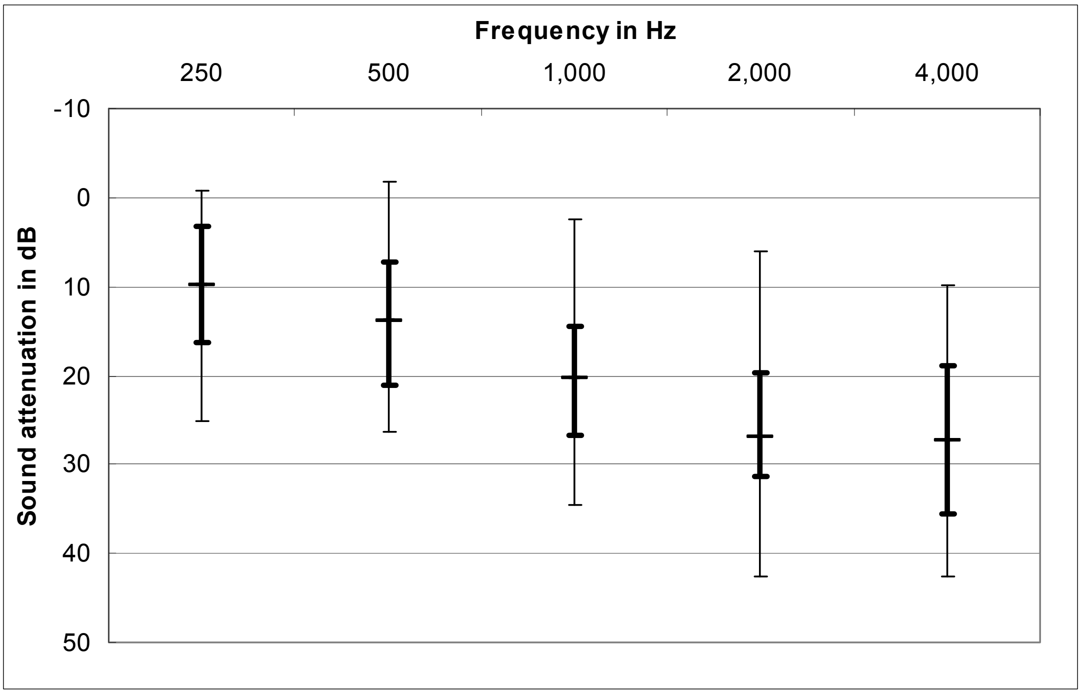


Figure A.7:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "Moldex Rockets Cord" pre-formed ear-plug (27 data records)

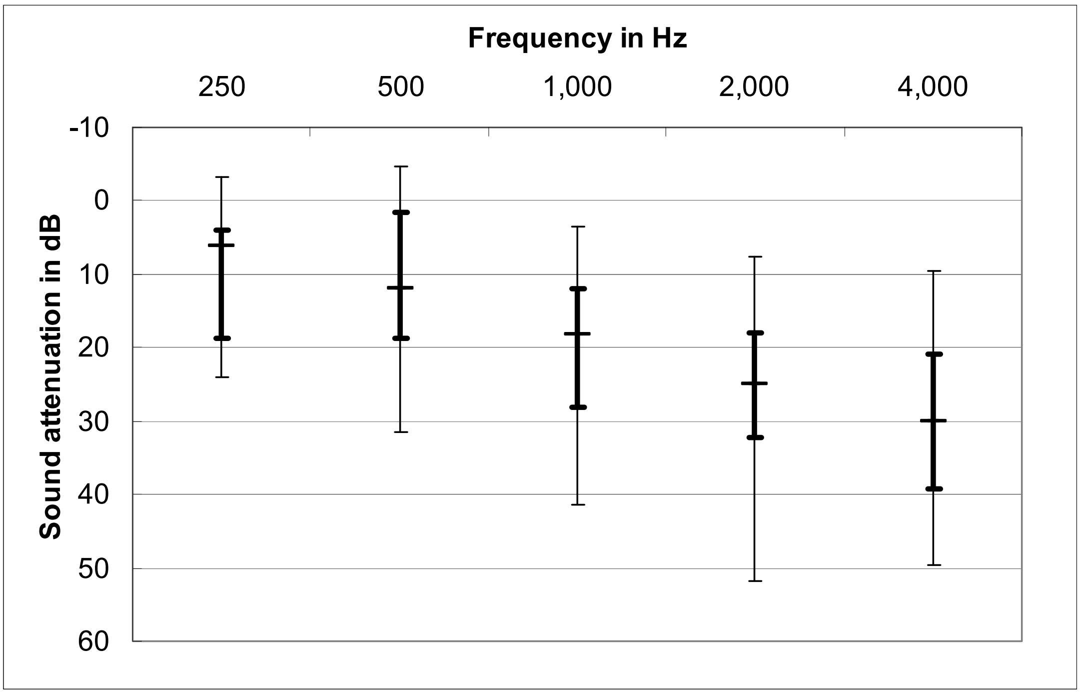


Figure A.8:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "Bilsom PerCap" headband ear-plug (30 data records)

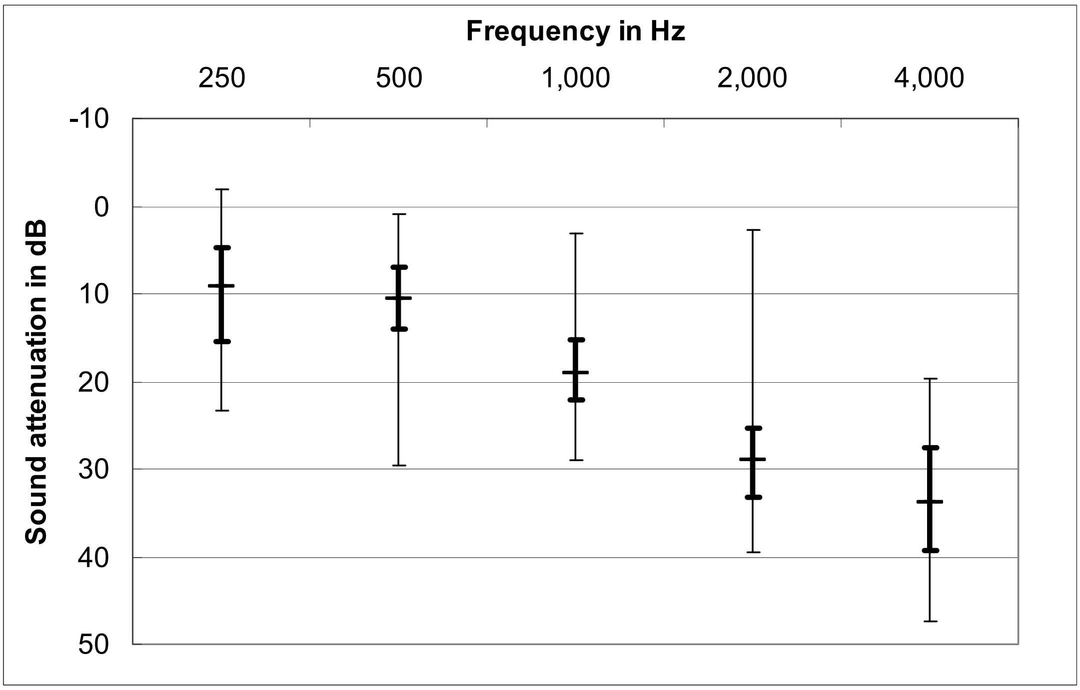


Figure A.9:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "E-A-R Flexicap", headband ear-plug, worn under the chin (33 data records)

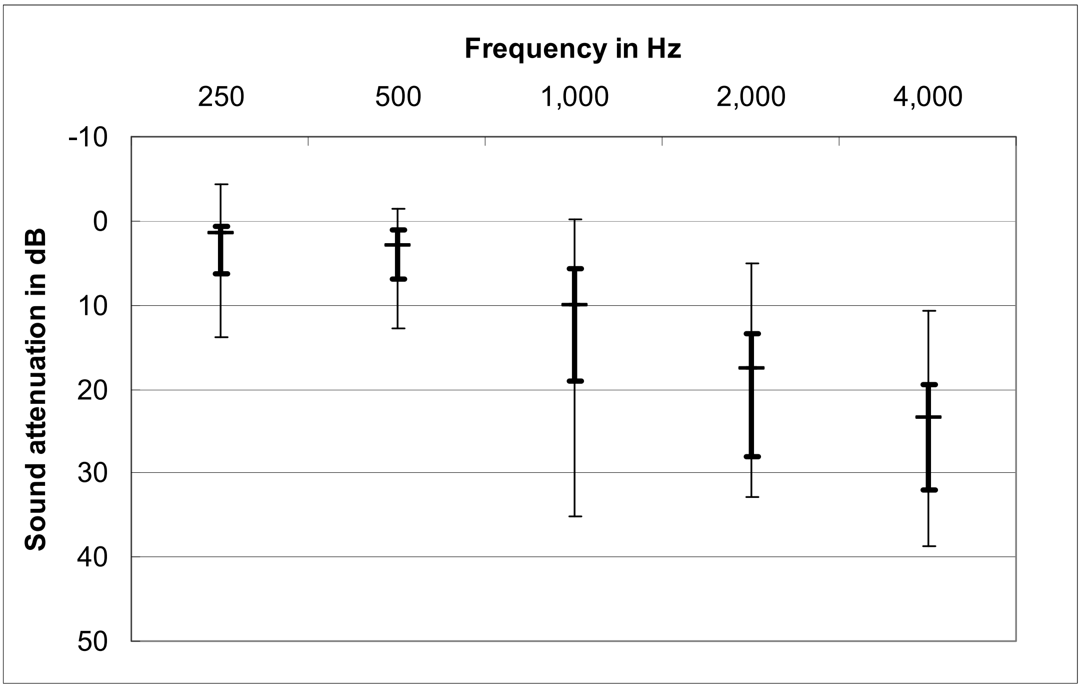


Figure A.10:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "Bilsom Viking V2" ear-muff (33 data records)

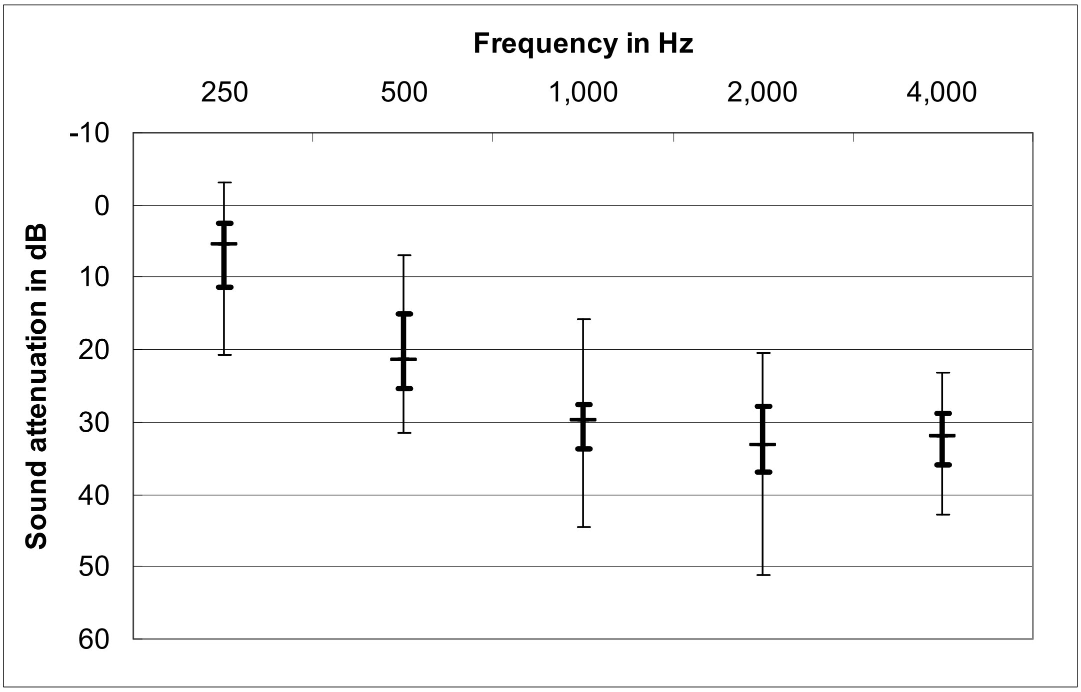


Figure A.11:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "Sicom" custom moulded ear-plug (60 data records)

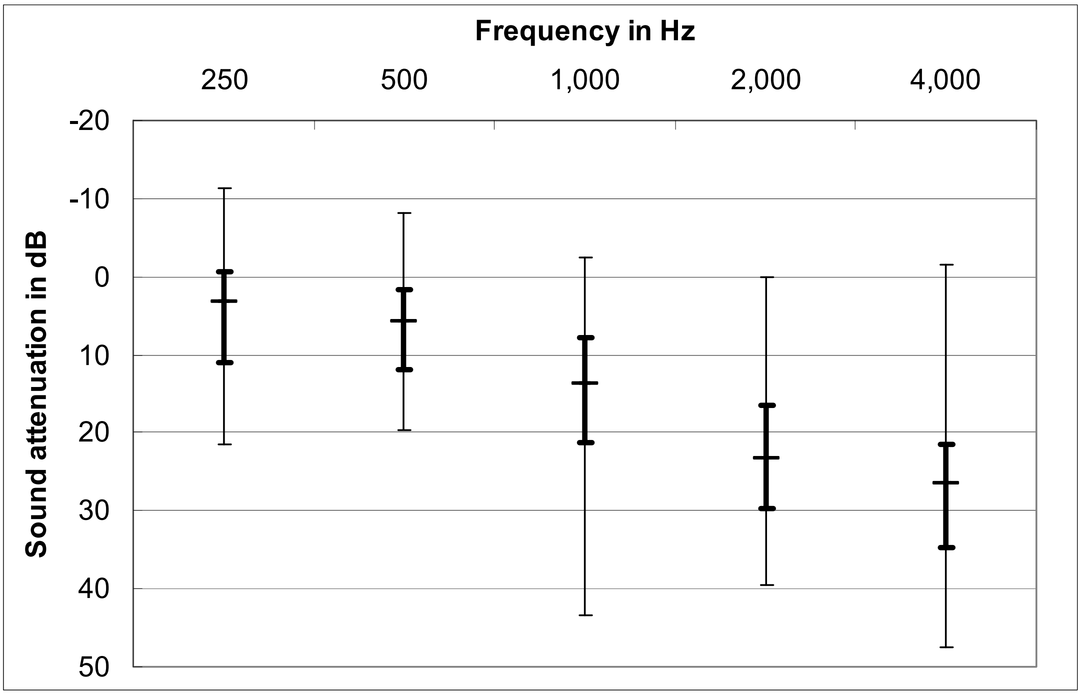


Figure A.12:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "Uvex HighFit F10" custom moulded ear-plug (69 data records)

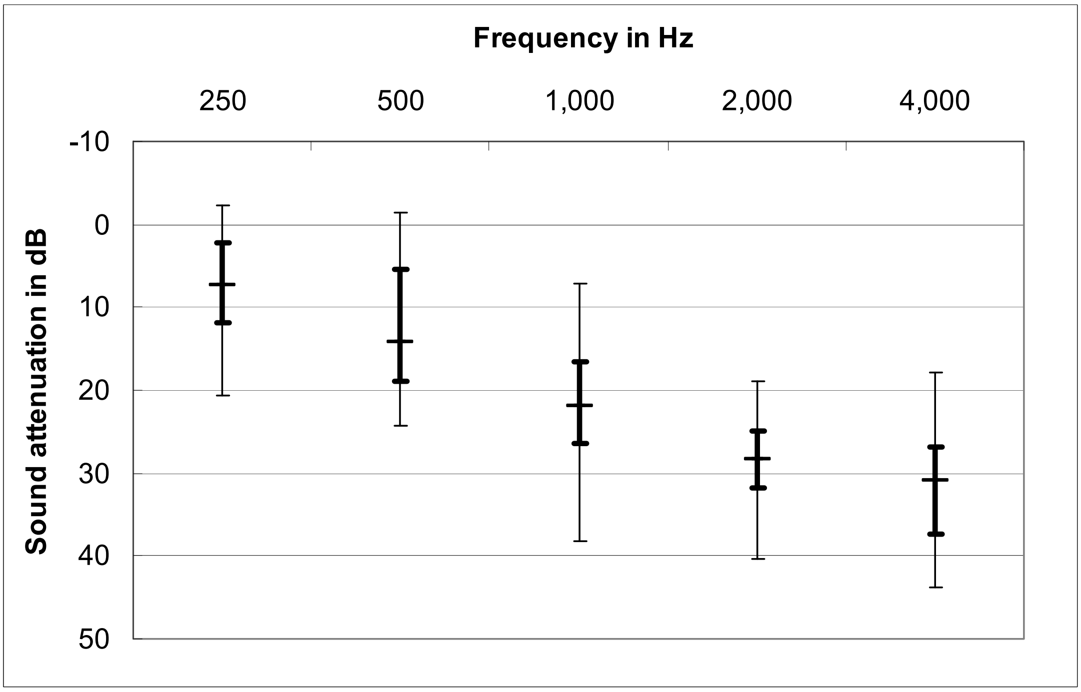


Figure A.13:
Median, 5th, 25th, 75th und 95th percentiles of the raw data measured in the audiomobile for "Sonus AS" custom moulded ear-plug (11 data records)