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**Transfer Characteristics of Headphones**

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**AN AUDIO ENGINEERING SOCIETY PREPRINT**

# TRANSFER CHARACTERISTICS OF HEADPHONES: MEASUREMENTS ON 40 HUMAN SUBJECTS

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## Summary

*In binaural technique, information on the transfer characteristics of the headphone used for reproduction is required. In the present investigation, headPhone Transfer Functions (PTFs) from voltage at the headphone terminals to sound pressure at the entrance to the blocked ear canal were measured. Data on the acoustical loading at the measuring point were also obtained. 14 headphones were measured on 40 human subjects.*

## 0. Introduction

The use of headphones has increased in recent years. The most frequent use is for reproduction of signals that were originally intended for a traditional loudspeaker stereo setup.

Signals, which are specifically suitable for headphone reproduction, are binaural signals, usually artificial head recordings. In the present investigation, data are collected with the purpose of obtaining correct reproduction of binaural signals through headphones. However, the data will be relevant for most situations, where sound is reproduced through headphones.

### 0.1 Binaural technique

The idea behind the binaural technique is the following. The input to the hearing consists of two signals: sound pressures at each of the eardrums. If these are recorded in the ears of a listener and reproduced exactly as they were, then the complete auditive experience is assumed to be reproduced, including timbre and spatial aspects. Normally, during recording, the listener is replaced by an artificial head



that has the same shape and the same acoustical properties as an average human head.

In binaural technique an effective separation of the two channels is crucial, and among the means for sound reproduction, only headphones offer this.

### 0.2 Previous measurements of headphone characteristics

It is difficult to obtain detailed information about headphones performance on real ears. Many headphone measurements are performed on various artificial ears, and most information is only given as amplitude responses, sometimes averaged over ⅓ octave frequency bands [1] [2] [3].

Results are frequently given as deviation between the sound pressure produced by the headphone and sound pressure produced at the same point in the ear canal by other means, usually a free field or a diffuse field exposure [4]. Such methods are well suited for obtaining a measure of the headphone's ability to replicate free field or diffuse field reproduction. For the use of headphones as means for reproduction of traditional stereo recordings, a diffuse field reference has most recently proven superior [2] [3], while different free field situations were used as reference in earlier research [5].

Data given in the above mentioned way are unsuitable for use in binaural technique, where the design goal is a flat frequency response from voltage at the headphone terminals to the recording point in the ear canal - denoted the reference point [6].

As for the specific measuring techniques used, a critical point is the choice and placement of the microphone. In some investigations it has been assumed that the sound pressure is uniform within the ear canal and the cavity enclosed by the headphone [7]. This is true for lower frequencies, but not for frequencies where the wavelength is comparable to the dimensions of the volume enclosed by the headphone.

### 0.3 Model of sound transmission

Headphone transfer functions depend on the choice of measurement point in the ear canal, individual parameters of the human ear, and - of course - the specific headphone. A previous work by Møller [6], describes the total transmission from a sound source to the listeners eardrums in a binaural system. The transmission during headphone playback is described by the model given in Figure 1.

The headphone is modelled by the Thevenin sound pressure at the entrance to the ear canal. This pressure does not normally exist physically, but if the ear canal is blocked, for example with an earplug placed with its outer end flush with the entrance to the ear canal, the Thevenin pressure is found at the outer side of the earplug.

The voltage at the headphone terminals is called $e_{headphone}$. The Thevenin pressure is called $p_5$, and the Thevenin source impedance is called $Z_{headphone}$. The sound pressure at the entrance to the ear canal (when it is not blocked) is denoted $p_6$. The ear canal acts as an acoustical transmission line terminated by the eardrum impedance $Z_{eardrum}$, and the pressure at the eardrum is denoted $p_7$ (in order to keep the same indices as in other articles on the same subject [6] [8] [9], indices 1 to 4 are not used).

Throughout the present paper, small letters are used to denote signals in the time domain, while capital letters denote the corresponding signals in the frequency domain. For instance, $P_5$ denotes the frequency domain representation of $p_5$.

Binaural recordings may be made at any point in the ear canal. However, recording of the Thevenin pressure at the entrance to the blocked ear canal has some advantages [6] [9]. When the binaural recording is made outside a blocked ear canal, it can be shown that - under certain conditions - the correct eardrum signals are obtained during playback, if the electrical gain of the transmission is:

$$G = \frac{1}{M \cdot [P_5/E_{headphone}]} \tag{1}$$

M is the microphone sensitivity, and $[P_5/E_{headphone}]$ is the frequency response measured at the entrance to the blocked ear canal [6]. In this paper $[P_5/E_{headphone}]$ is denoted headPhone Transfer Function (PTF) (PTF in order to prevent from confusion with Head-related Transfer Function (HTF)).

The assumptions that must be made in order to obtain (1), is that the pressure division between $Z_{headphone}$ and $Z_{ear\ canal}$ is equal to the corresponding pressure division during recording. At that time, $Z_{headphone}$ is replaced by the free field radiation impedance. Information about the pressure division in the free field is available from a parallel work in our laboratory by Hammershøi et al. [9].

### 0.4 Goal of present investigation

It is the purpose of the present investigation to determine PTFs $[P_5/E_{headphone}]$ for a number of commercially available headphones, measured on a large number of subjects.

Furthermore, it is the purpose to find the pressure division $[P_6/P_5]$ between $Z_{ear\ canal}$ and $Z_{headphone}$, and to compare that to similar data for the free field situation.

## 1. Method

Measurements were carried out with 14 headphones placed at the ears of 40 subjects. Impulse responses were measured for the transmission from voltage at the input of the power amplifier to output of the measuring microphone, placed to measure $p_5$ or $p_6$.



The impulse responses were measured with maximum length sequence (MLS) technique, and a master-slave configuration of two measurement systems enabled simultaneous measurements at both ears. PTFs and pressure divisions $[P_6/P_5]$ were obtained through Fourier transformation of the measured impulse responses, followed by appropriate divisions.

For each subject and each headphone, three measurements were made. $p_5$ was measured with an electret microphone, and both $p_5$ and $p_6$ were measured with a probe microphone.

### 1.1 Subjects

40 subjects participated, 22 male and 18 females. 31 were randomly chosen students and 9 were staff members. All subjects had controlled normal hearing, and furthermore none had reported ear abnormalities that might affect the middle ear function. The same subjects participated in a parallel investigation of free field head-related transfer functions [9].

### 1.2 Microphones

The choice of microphone for measurement in the human external ear is a compromise between having a satisfying sensitivity and a microphone of acceptable dimensions. For measurement of the Thevenin pressure $p_5$ a Sennheiser KE 4-211-2 miniature microphone was used. This is an electret microphone, cylindrical in shape Ø 4,75 mm × 4,20 mm, see photo in Figure 2.

The KE 4-211-2 is a pressure microphone of the back electret type, and it has a built-in FET amplifier. The microphone itself has a sensitivity of approximately 10 mV/Pa. Coupled with a gain as suggested in the data sheet, the sensitivity increases to approximately 35 mV/Pa. A small battery box was designed, and in order to increase the output signal and to reduce the output impedance, a 20 dB amplifier was built into the same box. Two selected microphones were used throughout the experiment, one for each ear. The frequency responses of these microphones including the front-end amplifiers are given in Figure 3.

During measurement of $p_5$ the microphone was mounted in an EAR earplug placed in the ear canal. The microphone was inserted in a hole in an earplug, and then the soft material of the earplug was compressed during insertion in the ear canal. As the earplug relaxed, the outer end of ear canal was completely filled out. The end of the earplug and the microphone were mounted flush with the ear canal entrance. The placement of the microphone is sketched in Figure 4, and a photo given in Figure 5.

During measurement of $p_6$ at the entrance to the open ear canal, the microphone could not be concealed in an earplug. It was estimated that the miniature microphone was so big that it would disturb the sound field. For measurement of $p_6$ a probe microphone was therefore used. This type of microphone would not disturb the measurement, since the interference of the probe tip is minimal, but it has the disadvantage of a low sensitivity. The probe microphone chosen was a B&K 4182 with a 45 mm metal tube extended by a short piece of flexible tube. The sensitivity of the probe microphone was approximately 3 mV/Pa, and frequency responses with a 50 mm metal tube are seen in Figure 6.

The probe microphone was attached to the external ear by a flexible metal strap. The strap and the flexible tube were individually adjusted to fit the shape of the external ear. To avoid displacement of the probe microphone during the experiment it was fixed along the subject's neck with tape, and the position of the tip was controlled before and after each single measurement.

In order to reduce the post processing of data needed for determination of $[P_6/P_5]$, and thereby reducing the possible sources of errors, $p_5$ measurements were also carried out with the probe microphone. It might then be argued that $p_5$ measurements with the miniature microphone only gave redundant information, and that they were unnecessary. However, the placement of the larger microphone was considered more well defined. Furthermore determination of PTF through two independent measurements was beneficial as an extra possibility of verifying the experimental technique.

The placement of the probe tip turned out to be critical during $p_5$ measurements, where the ear canal was blocked by an earplug, and the tip could be occluded when the headphone was put on. To avoid occlusion of the probe tip, the metal tube was extended by a short piece of flexible tube (made of silicone), so that the tip only bent slightly, when the headphone was put on. Additionally, a small paper label was attached to the soft and rough surface of the earplug, and occlusion was avoided. The placement of the probe microphone with the ear canal blocked and unblocked is sketched in Figure 7. The photo in Figure 8 shows, how the probe microphone is attached to the subject's ear and neck.

In order to minimize the error due to displacement of the probe tip between measurement of $p_5$ and $p_6$, the probe measurements were carried out in the following way: $p_5$ was measured first. Then the earplug was carefully removed with as little disturbance of the probe microphone as possible. Immediately afterwards $p_6$ was measured.

### 1.3 Headphones under test

Transfer characteristics were determined for 14 headphones, of which the manufacturer's specifications are given i Table I. A few comments should be connected to four of these.

Headphone number 1 is not an ordinary headphone, but two small loudspeakers placed close to the subject. The loudspeakers used were 7 cm diameter midrange units (Vifa M10MD-39) mounted in 15,5 cm diameter hard plastic balls. The specific setup with distances and angles of incidence to the subject is sketched in Figure 9 and shown in a photo in Figure 10. In addition to PTF, the cross-talk in this specific setup was measured.



One headphone is electrostatic (number 11), and the measurements include the gain of a dedicated class A power amplifier with the volume control at an arbitrary but fixed level.

Headphone number 13 and 14 are essentially the same headphone, but with two different positions of the sound producing units. Measurements were made with a distance of 2 cm from the fixed part of the headphone to the adjustable part (number 13) and with the maximum angle obtainable (number 14). For a few subjects, the headphone touched pinna without deforming it in the first position, while it was always free from the pinna in the second position.

### 1.4 Measuring setup

The general purpose measuring system known as MLSSA (Maximum Length Sequence System Analyzer) was used. Maximum Length Sequences are binary two level pseudo-random sequences. The basic idea of MLS technique is to apply an analogue version of the sequence to the linear system under test, sample the resulting response, and then determine the system impulse response by cross-correlation of the sampled response with the original sequence.

The method offers a number of advantages compared to traditional frequency and time domain techniques. The method is basically noise immune, and combined with averaging, the achieved signal to noise ratio is high. A thorough review of the MLS method is given by Rife and Vanderkooy [10].

For the purpose of measuring at both ears simultaneously, two MLSSA systems were used, coupled in a master-slave configuration by a purpose made synchronization unit allowing sample synchronous measurements. A sketch of the complete measuring setup is given in Figure 11. The MLSSA systems were set up with autorange enabled, allowing the best possible utilization of the dynamic range.

The stimulus signal from the master MLSSA board was sent to the power amplifier (Pioneer A-616) that was modified to have a calibrated gain of 0,0 dB. From the output it was directed to the headphone being tested. The stimulus amplitude was determined to cause approximately the same A-weighted sound level in the ears of a head and torso simulator B&K 4128 as the free field stimulus in a parallel investigation of free field head-related transfer functions [9] (free field level approximately 75 dB(A), ear level with frontal incidence of the sound wave, approximately 88 dB(A)). The reason for this choice was to have approximately the same conditions in the two investigations and to have a level where the stapedius is assumed to be relaxed. Ear levels between 80 and 90 dB(A) were obtained with stimulus amplitudes between ± 0,06 V and ± 0,68 V applied to the different headphones.

From the microphone (miniature as well as probe) the signal was sent through a measuring amplifier, B&K 2607. The output signal from the measuring amplifier was attenuated by a factor of 2 in order to adjust the dynamic range of the signal to the input range of the MLSSA board. The probe microphones were powered by a power supply B&K 2804, since there were no cables for transferring the power and polarization voltage lines from the measuring amplifier to the measuring room. The microphone sensitivities at 1 kHz were measured every work day during the two month measurement period, and deviations from the nominal value were below ± 0,3 dB.

The sampling frequency of 48 kHz was provided by an external clock. To avoid frequency aliasing, the 20 kHz Chebyshev low pass filter of the MLSSA board and the 22,5 kHz low pass filter of the measuring amplifier were used. Also the 22,5 Hz high pass filter on the measuring amplifier was active.

It is a prerequisite, that the MLS sequence used in a measurement is longer than the impulse response of the system under test. In the present setup for headphone measurements, this is easily satisfied with the minimum length offered in MLSSA, which is 4095 points. In order to achieve a high signal to noise ratio, the recording was averaged 16 times, called pre-averaging in the MLSSA system. Even with this averaging the total time for a measurement was as short as 1,45 seconds. All measured impulse responses were very short, and only the first 768 samples of each impulse response - corresponding to 16 ms - were computed and saved.

### 1.5 Data processing

Results of the measurements were impulse responses for the transmission from input to the power amplifier to output of the measuring amplifier. In order to obtain the wanted information, some post processing was needed. This was carried out in MATLAB.

All impulse responses were very short, duration only a few milliseconds. Therefore, only the first 256 samples were used in the post processing (time from 0 to 5,33 ms).

For determination of the pressure division $[P_6/P_5]$, the impulse responses to $p_5$ and $p_6$ were Fourier transformed, and a complex division was carried out in the frequency domain. As the same equipment was involved during measurement of $p_5$ and $p_6$, the influence of equipment cancels out. Here it is important that both measurements were made with the probe microphone.

It is slightly more complicated to find $[P_5/E_{headphone}]$, since that requires - at all frequencies - a calibration of the conversion between voltage and pressure. The impulse response measured during measurement of $p_5$ was Fourier transformed and the frequency response $H_{measured}$ obtained. In addition to $[P_5/E_{headphone}]$, $H_{measured}$ includes the transfer function of the electrical components $H_{electrical}$ and the microphone transfer function $M_{KE\ 4\text{-}211\text{-}2}$.

It was straightforward to measure $H_{electrical}$ by short circuiting. $M_{KE\ 4\text{-}211\text{-}2}$ was found through reference to a microphone with known frequency response. A B&K 4136 ¼ inch microphone was chosen, since it has an approximately flat free field response in the frequency range of interest for 90° incidence (deviation +0,7 dB at 15 kHz, +1,2 dB at 20 kHz). The free field response of a loudspeaker was measured with the two microphones, one at a time in the sound field. The two impulse responses were Fourier transformed and a complex division was made in the frequency domain. This gave the ratio $M_{KE\ 4\text{-}211\text{-}2}/M_{B\&K\ 4136}$, since all other equipment was the same during these two measurements. $M_{KE\ 4\text{-}211\text{-}2}$ was then obtained by multiplication with the nominal sensitivity of the B&K 4136 microphone.

The wanted transfer function was found as

$$[P_5/E_{headphone}] = \frac{H_{measured}}{H_{electrical} \cdot M_{KE\ 4\text{-}211\text{-}2}} \qquad (2)$$

For the determination of $[P_5/E_{headphone}]$ and $[P_6/E_{headphone}]$ when measured with the probe microphone, $M_{KE\ 4\text{-}211\text{-}2}$ was replaced by the frequency response of the probe microphone $M_{B\&K\ 4182}$. $M_{B\&K\ 4182}$ was determined in a procedure similar to the determination of $M_{KE\ 4\text{-}211\text{-}2}$. However, the free field stimulation for the comparison was replaced by a pressure chamber stimulation as described in the B&K 4182 manual. The same B&K 4136 microphone, having a flat pressure frequency response up to 50 kHz, was used for reference.

### 1.6 Signal to noise ratio

The signal to noise ratio cannot be expressed as a single figure, since it depends on the response being measured. For illustration, the total noise level was found by repeating a measurement, but with the headphone electrically replaced by a resistor. All gain settings were as in the original measurement. Examples with the two types of microphones are given in Figure 12 and Figure 13. The signal to noise ratio is typically around 70 dB and never below 50 dB for the miniature microphones. For the probe microphones corresponding figures are approximately 10 dB lower.

## 2. Results

At the time of submission of the manuscript, only processed data from 12 subjects were available. A thorough analysis will await the remaining data. Only examples of results are given in this section. Data are chosen by random and are not necessarily representative. The comments to the results should not be regarded as conclusive.

### 2.1 PTFs for the different headphones

The computed PTFs for the different headphones are shown in Figure 14a, b and c, as measured on the two ears of the same person. The difference between the two sides reflect differences in ear as well as difference between the two channels of the headphone.

A flat response measured at the reference point (here, the blocked ear canal) is desirable for the purpose of reproduction of binaural recordings, or a response which can be easily equalized. The headphones which come closest to this request (measured on one person) are those numbered 5 and 12. 8 and 11 have fairly smooth responses with no severe peaks or dips. Headphone number 2 has a high peak between 4 and 5 kHz, which may be correctable. Some headphones have frequency responses that appear difficult to equalize.

Another observation is, that the responses vary widely, even for the headphones which are claimed to follow a diffuse field characteristic. It must be noted here, that if the reader should feel tempted to compare the results with a known diffuse field characteristic (to get an ultimate answer on which headphone is "best"), is it important to choose a characteristic, which has been measured at the entrance to a blocked ear canal, as the measurements in the present investigation.

### 2.2 Pressure division

Apart from a flat frequency response, it is important, that the pressure division $[P_6/P_5]$ is similar to the pressure division in free field. Examples of both the pressure division in the reproduction situation and free field situation for one person is shown in Figure 15. Overlay is shown for all headphones, and the pressure division is generally comparable to the free field pressure division, although a few headphones seem to deviate for this person. The importance of analysis of the complete data material is stressed.

### 2.3 Inter-individual variation

Figure 16 gives an indication of the individual differences. The upper set of curves shows PTF for the left ear of 12 subjects for one headphone. Some variation is present, although a general shape is seen for the whole frequency range. However, the variation increases significantly above 7 kHz.

The inter-individual variation in the pressure division is illustrated in the middle set of curves, where $[P_6/P_5]$ is shown for the same 12 subjects. Here the variations are much larger, and they appear at frequencies from 2 kHz.

$p_6$ will reflect the individual variation of the transmission from voltage at the headphone terminals to $p_5$ as well as the individual variation in the pressure division. Therefore, the variation in $[P_6/E_{headphone}]$ is expected to be larger than the variation in $[P_5/E_{headphone}]$. This is exactly what is seen from the lower set of curves, where $[P_6/E_{headphone}]$ is shown.



### 2.4 Validity of results

A measure for the quality of the computed PTF's is found by comparison of the PTF's computed for $p_5$ measurements made with two different measuring techniques. These comparisons will reveal variations due to replacement of the headphones, inaccuracy in reaching the same reference point with two microphone techniques as well as inaccuracy in post processing.

Examples of PTFs computed for three headphones in the two different ways are given in Figure 17. The headphones chosen are basically different in terms of placement at the ear. There is excellent agreement in results up to 8 kHz and good agreement for the rest of the frequency range.

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[9] Dorte Hammershøi, Henrik Møller, Michael Friis Sørensen, Kim Alan Larsen: Head-related Transfer Functions: Measurements on 40 Human Subject. To be presented at the 92nd Convention of the Audio Engineering Society, Vienna, 1992.

[10] Douglas D. Rife, John Vanderkooy: Transfer-function measurement with maximum-length sequences. Journal of the Audio Engineering Society, vol. 37, no. 6, pp. 419-444, 1989.



| Headphone | Transducer principle | Physical position on ear | Frequency response (Hz) (correction) |
|---|---|---|---|
| #1 | Electrodynamic, open | Free of ear | - |
| #2 | Electrodynamic, open | Supraaural | - |
| #3 | Electrodynamic, open | Circumaural | 16-30k (diff.field) |
| #4 | Electrodynamic, open | Circumaural | 16-25k (diff.field) |
| #5 | Electrodynamic, open | Supraaural | 18-20k |
| #6 | Electrodynamic, closed | Circumaural | 10-25k (diff.field) |
| #7 | Electrodynamic, closed | Circumaural | 5-35k (diff.field) |
| #8 | Electrodynamic, open | Circumaural | 5-35k (diff.field) |
| #9 | Electrodynamic, open | Free of ear | 30-20k |
| #10 | Electrodynamic, open | Circumaural | 15-25k |
| #11 | Electrostatic | Circumaural | 8-35k (diff.field) |
| #12 | Electrodynamic, open | Circumaural | 20-20k (diff.field) |
| #13 | Electrodynamic, open | Free of ear | 30-25k |
| #14 | Electrodynamic, open | Free of ear | 30-25k |

Table I. The manufacturer's specifications for the headphones used.

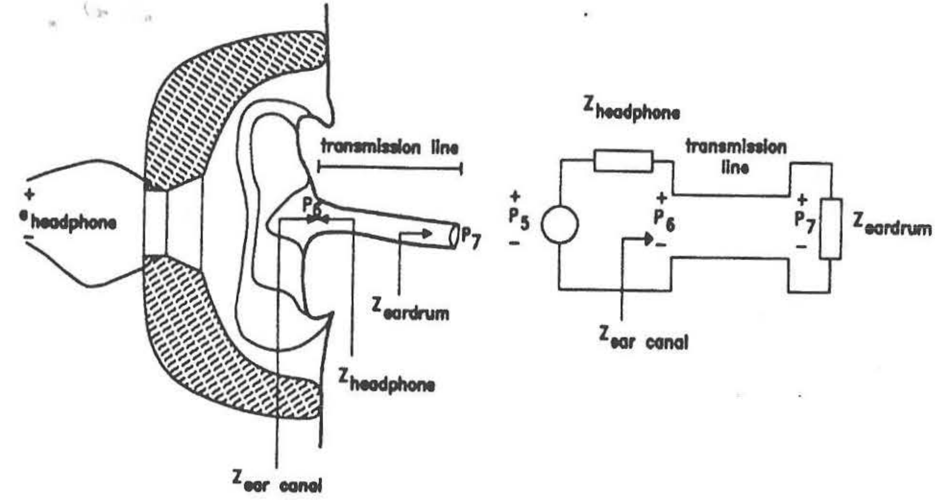


Figure 1. Left side of the figure shows an anatomical sketch of the headphone and the human external ear, and right side is an equivalent model as described by Møller [6].

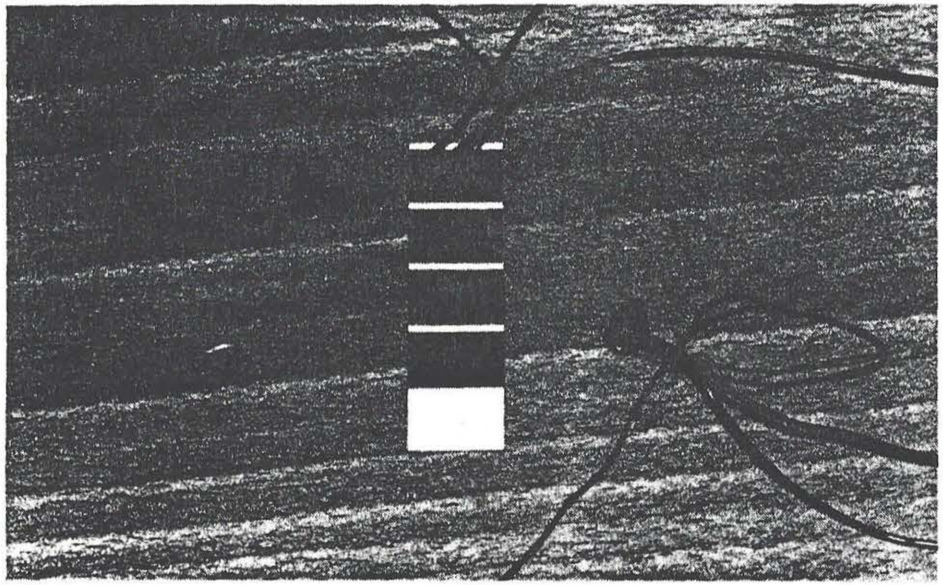

Figure 2. Photo of two miniature microphones, Sennheiser KE 4-211-2. The white lines indicate 1 cm intervals. Two soft electrical wires are connected by soldering at the back side. Additionally, a thread is mounted as an aid during the removal of the microphone from the ear canal. The microphone and the connections are protected by flexible heat-shrinkable tubing.



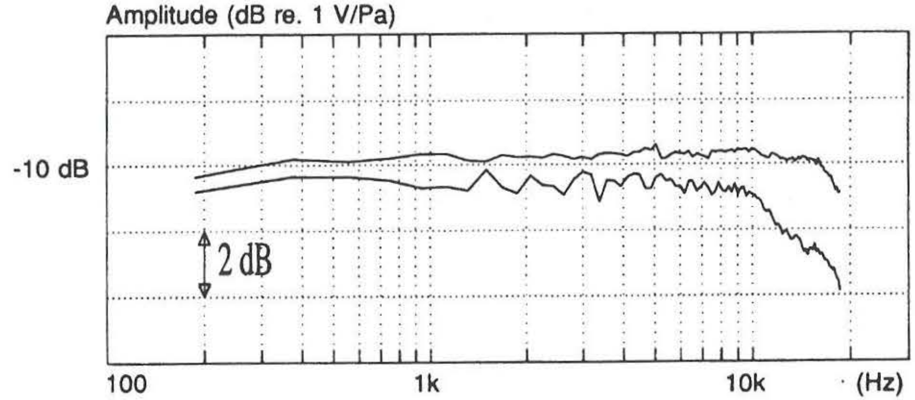


Figure 3. Frequency responses of the two miniature microphones, Sennheiser KE 4-211-2, including the front-end amplifiers.

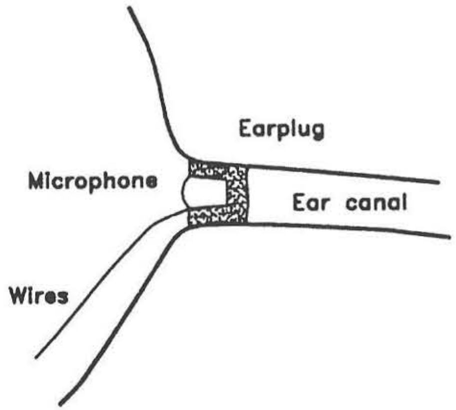


Figure 4. Sketch of the miniature microphone inserted in an earplug in the ear canal.

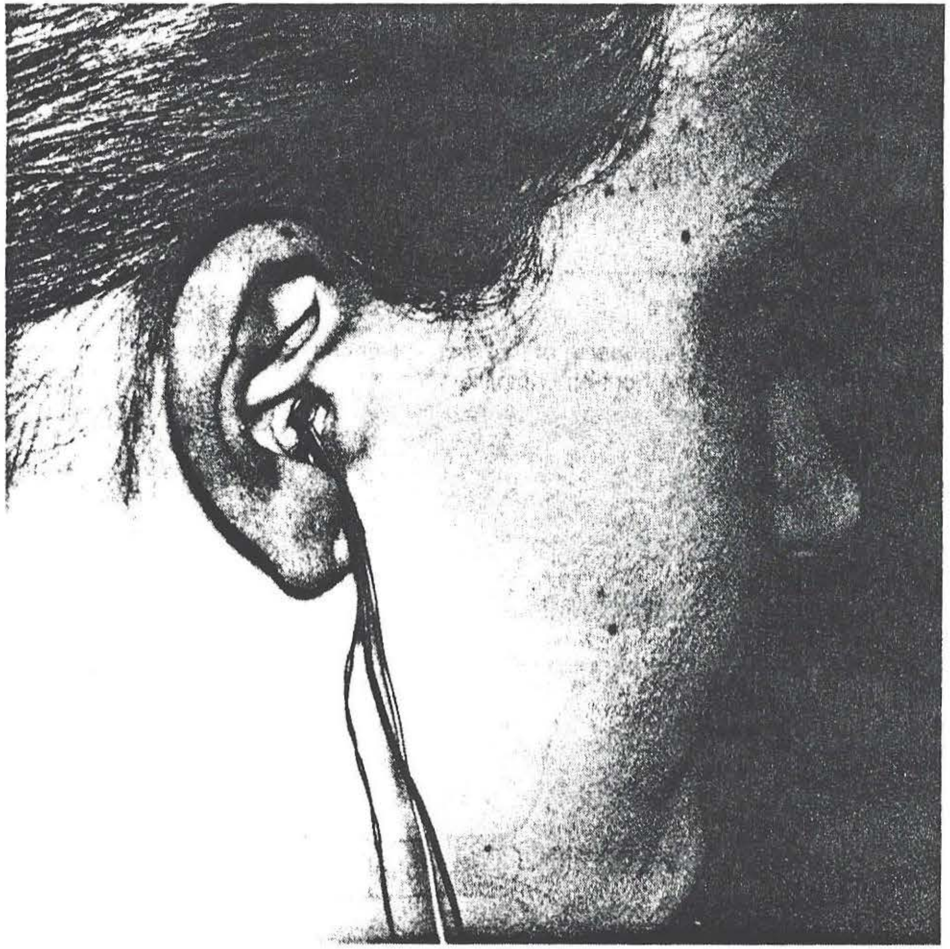

Figure 5. A photo of the miniature microphone, mounted in the ear of a subject.



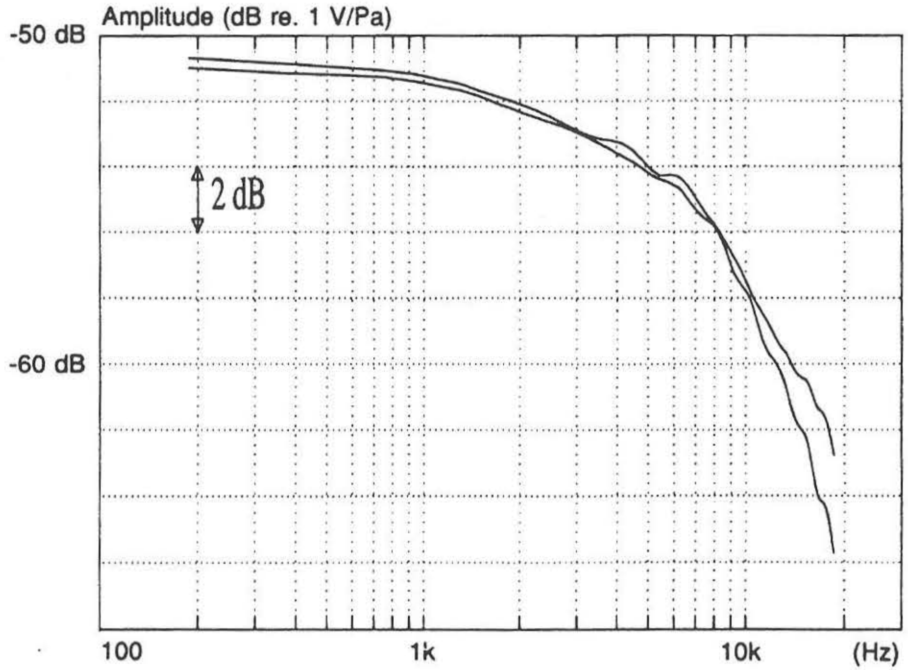


Figure 6. Frequency responses of the two probe microphones, B&K 4182, including a 50 mm metal tube.

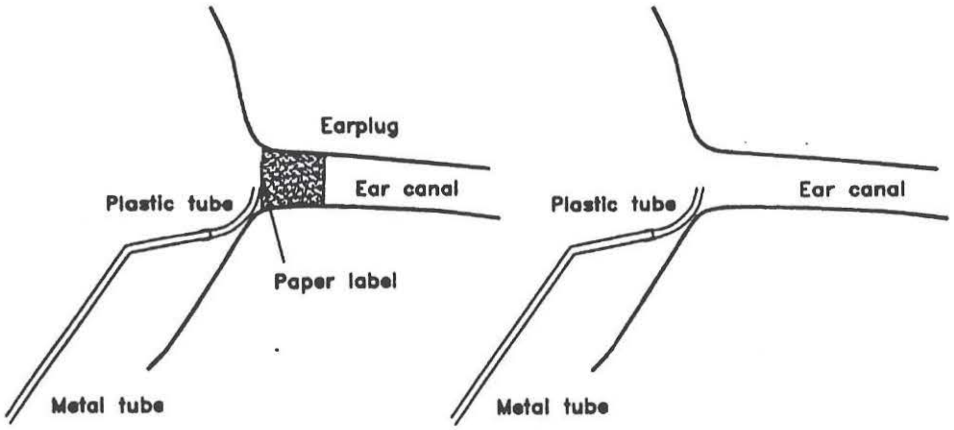


Figure 7. Sketch of placement of the flexible tube extending the metal tube of the probe microphone. Left side with the ear canal blocked using an earplug, right side with the ear canal unblocked.



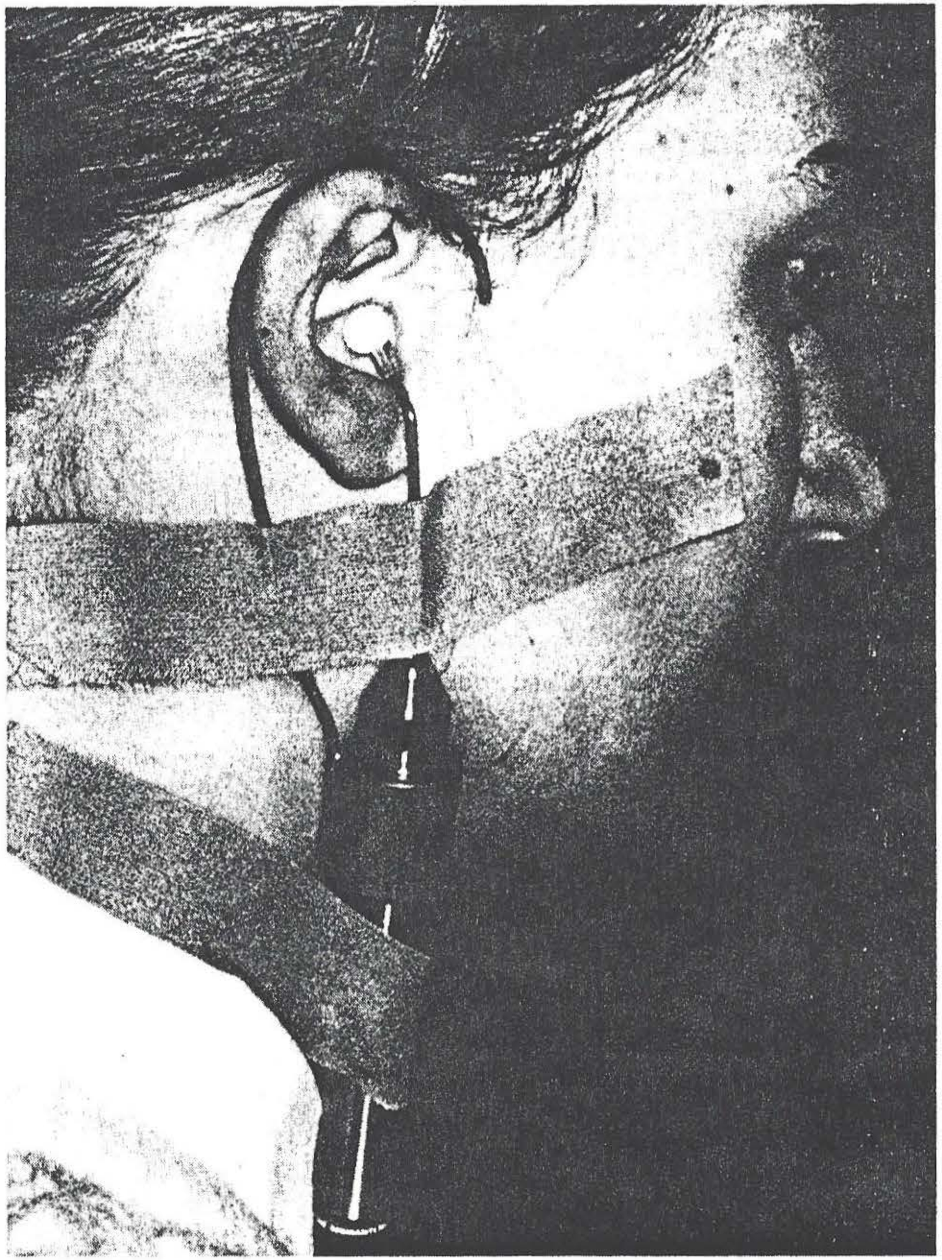

Figure 8. Photo of the probe microphone, mounted on a human subject.

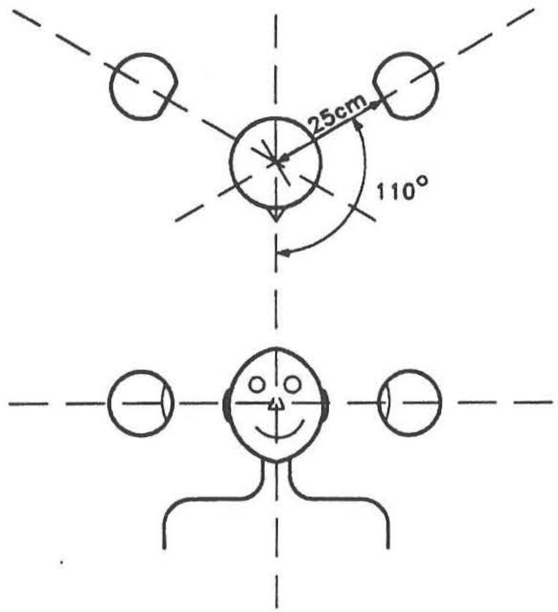


Figure 9. Sketch of the close mounted loudspeakers, "headphones" number 1.

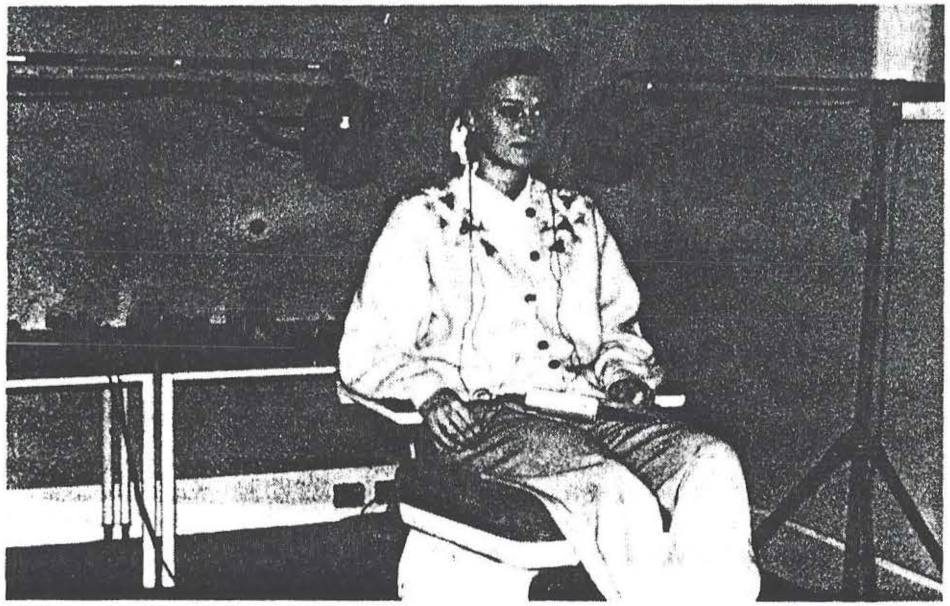

Figure 10. A photo of the close mounted loudspeakers, "headphones" number 1.



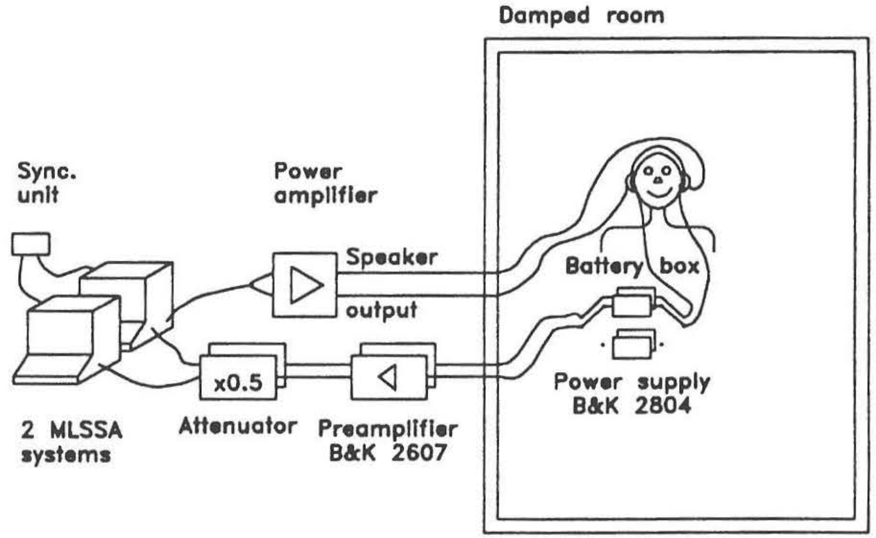


Figure 11. Sketch of the measuring setup.

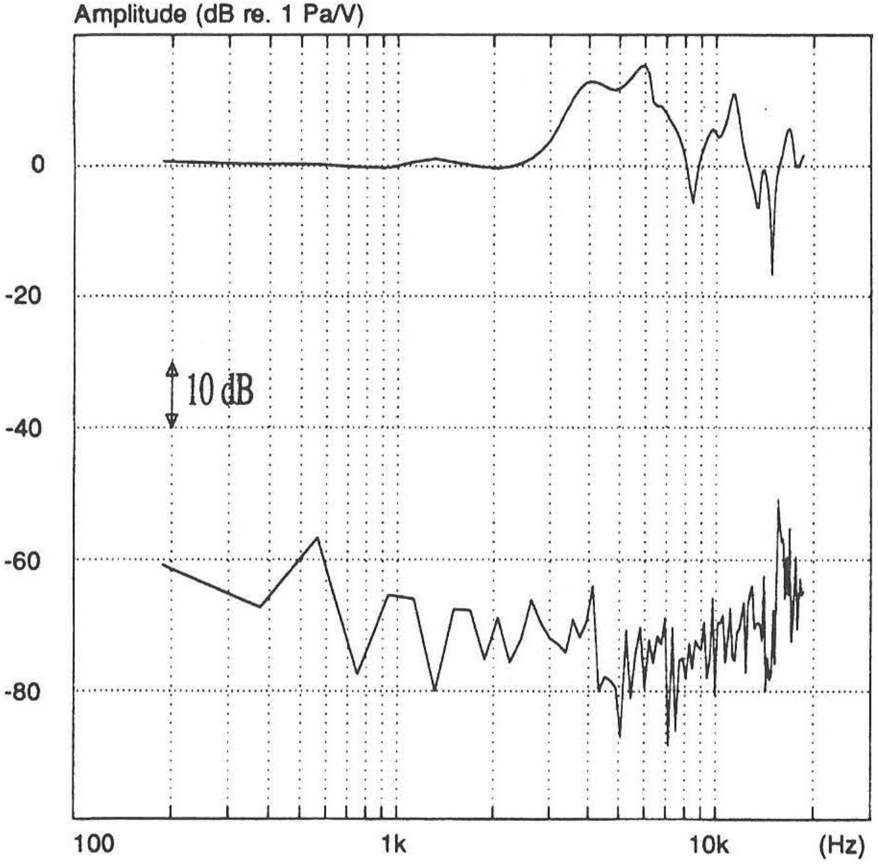


Figure 12. Illustration of signal to noise ratio. Upper curve shows a typical miniature microphone measurement, lower curve shows a measurement with all settings unchanged, but with the headphone replaced by a 100 Ω resistor. The signal to noise ratio (distance between the two curves) varies from 50 dB to more than 80 dB. It is emphasized that these data are original measurements not processed as described in equation (2). The headphone has a sensitivity of 1 Pa/V (by coincidence).



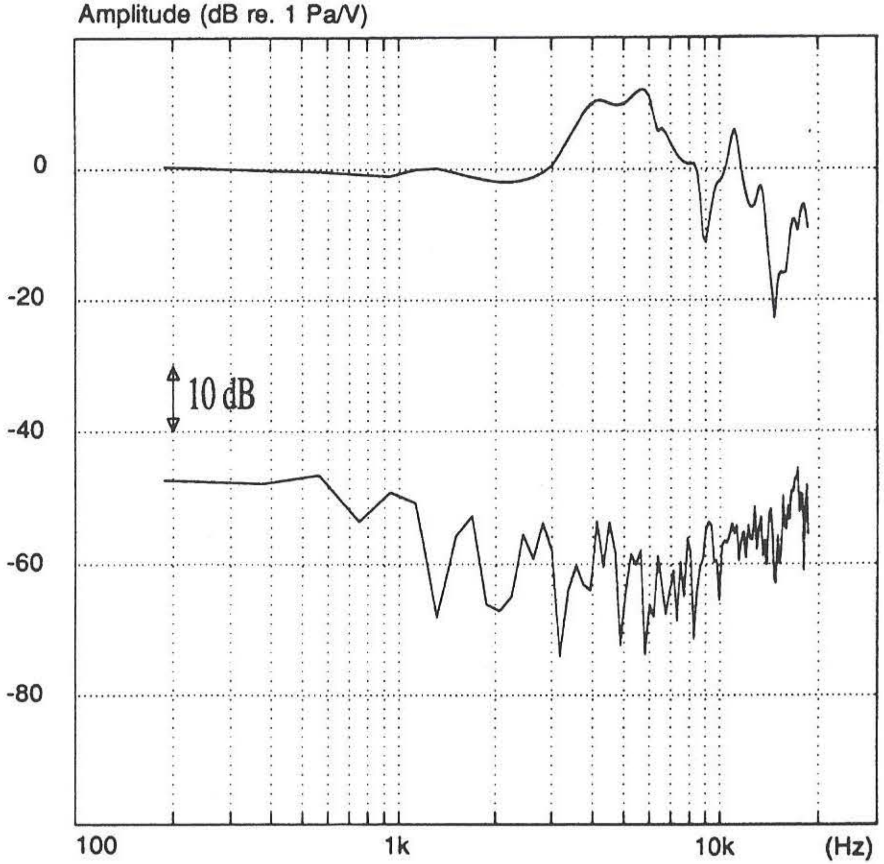


Figure 13. Illustration of signal to noise ratio. Upper curve shows a typical probe microphone measurement, lower curve shows measurement with all settings unchanged, but with the headphone replaced by a 100 Ω resistor. The signal to noise ratio (distance between the two curves) varies from 40 dB to more than 70 dB. It is emphasized that these data are original measurements not processed as described in equation (2). The headphone has a sensitivity of 1 Pa/V (by coincidence).

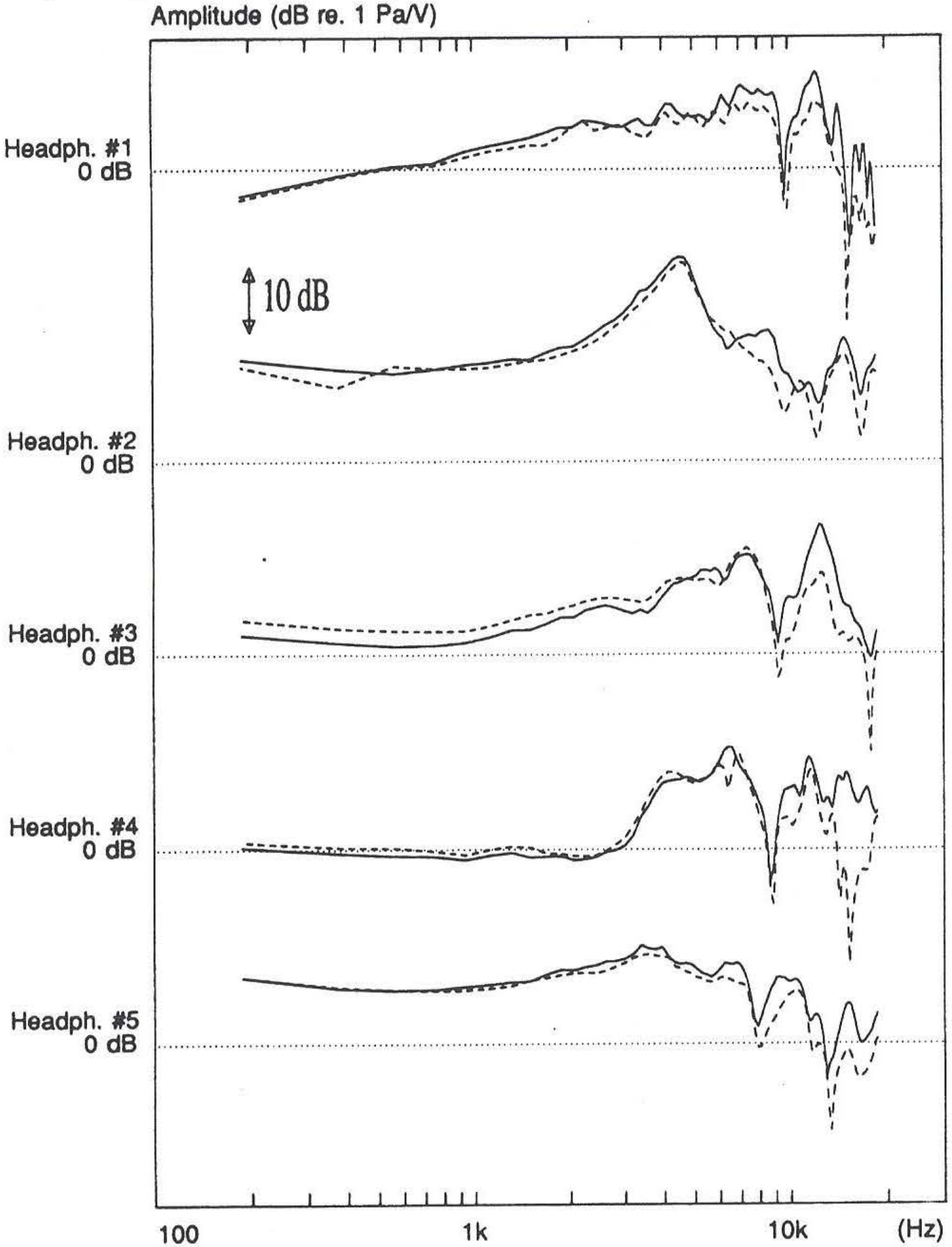


Figure 14a. PTFs for headphones numbered 1-5 for the same person. PTFs for left ear are shown with solid lines and PTFs for right ear are shown with dashed lines.



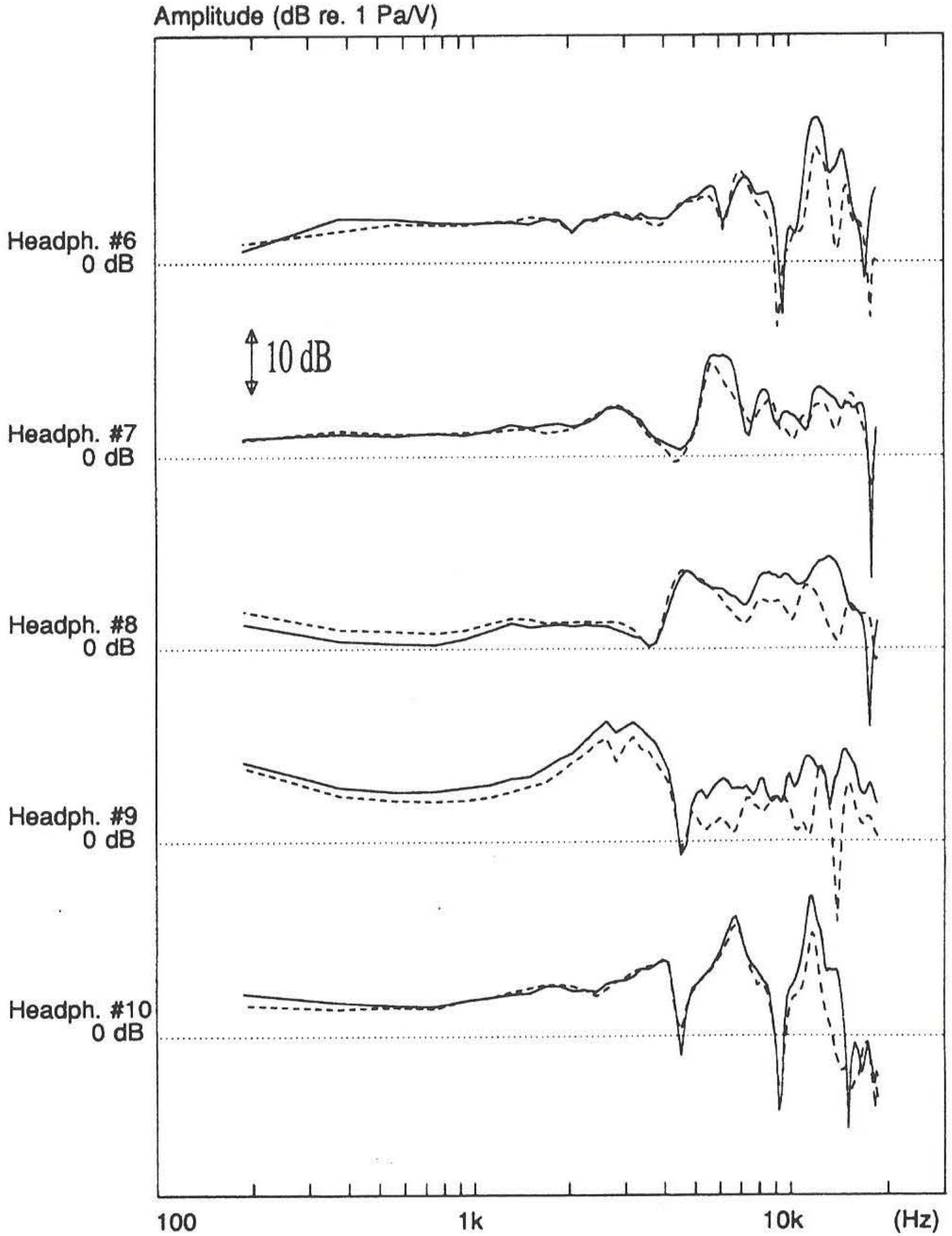


Figure 14b. PTFs for headphones numbered 6-10 for the same person. PTFs for left ear are shown with solid lines and PTFs for right ear are shown with dashed lines.

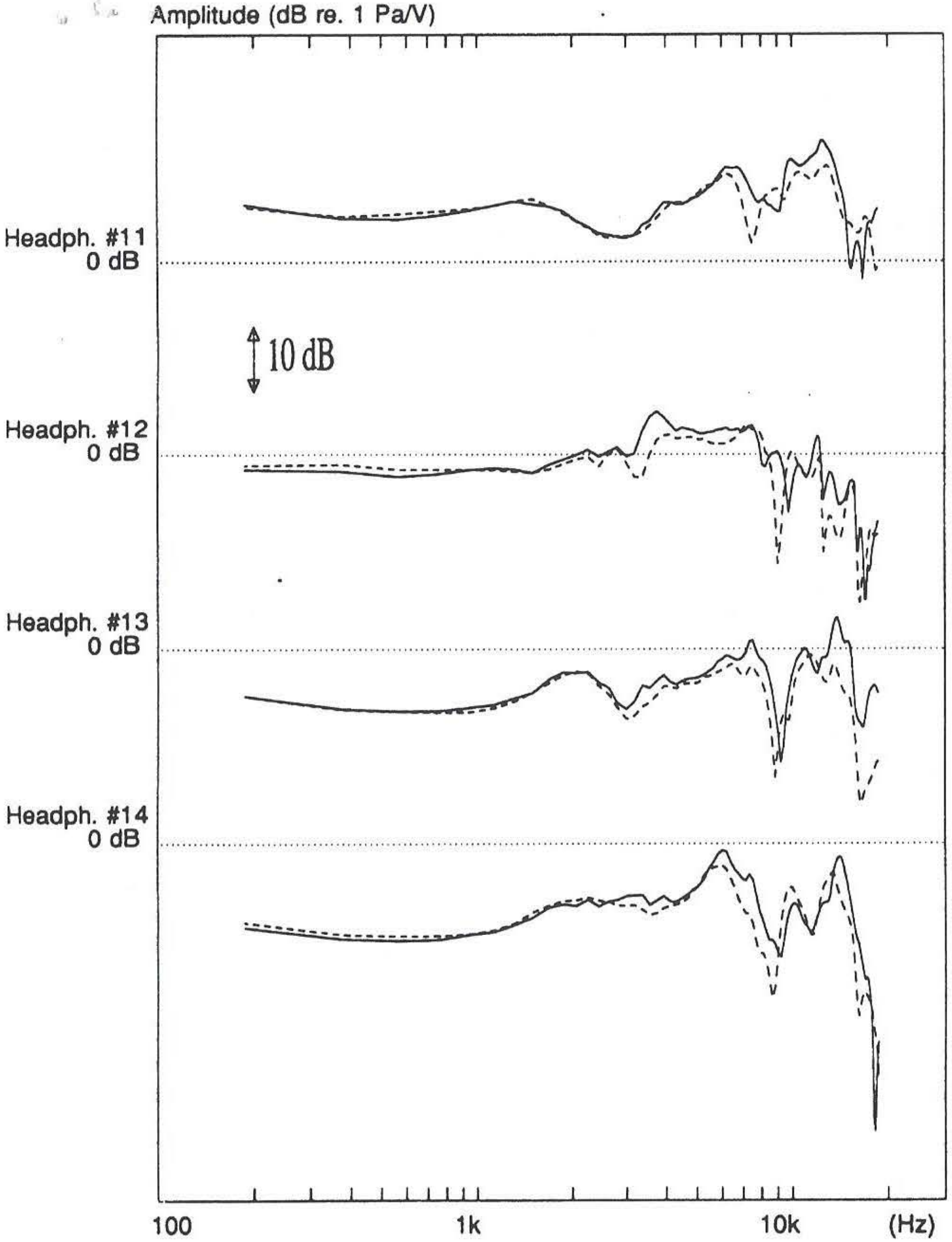


Figure 14c. PTFs for headphones numbered 11-14 for the same person. PTFs for left ear are shown with solid lines and PTFs for right ear are shown with dashed lines.



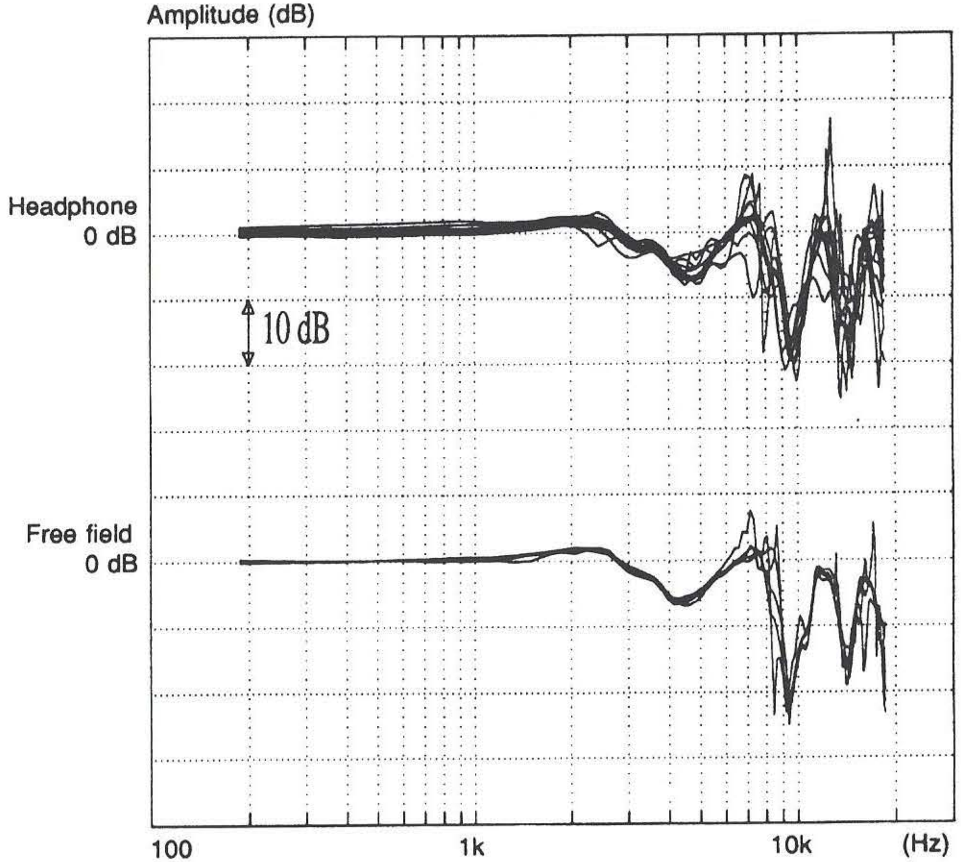


Figure 15. The pressure division at the reference point. Upper 14 curves show the pressure division for one person, left ear, with the different headphones applied. Lower 5 curves show the pressure division in the free field situation of the same person, same ear, with incidence of the sound wave being front, back, left, right and above (data from Hammershøi et al. [9]).

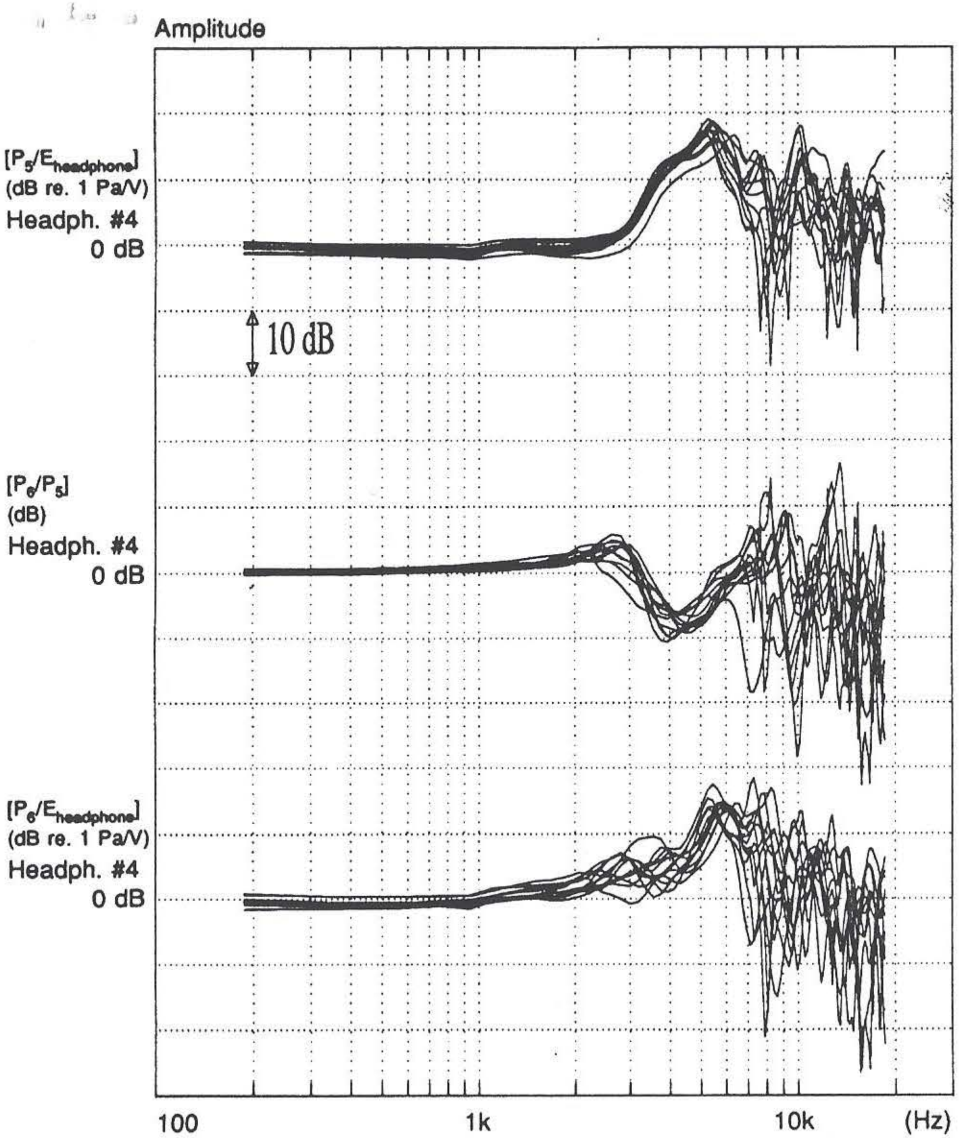


Figure 16. Individual variation in headphone frequency responses (preliminary results) for a randomly chosen headphone, left ear of 12 persons. Upper set of curves show $[P_5/E_{headphone}]$, middle set of curves show $[P_6/P_5]$ and lower set of curves show $[P_6/P_{headphone}]$. All responses are based on measurements made with the probe microphone. The headphone has a sensitivity of 1 Pa/V (by coincidence).



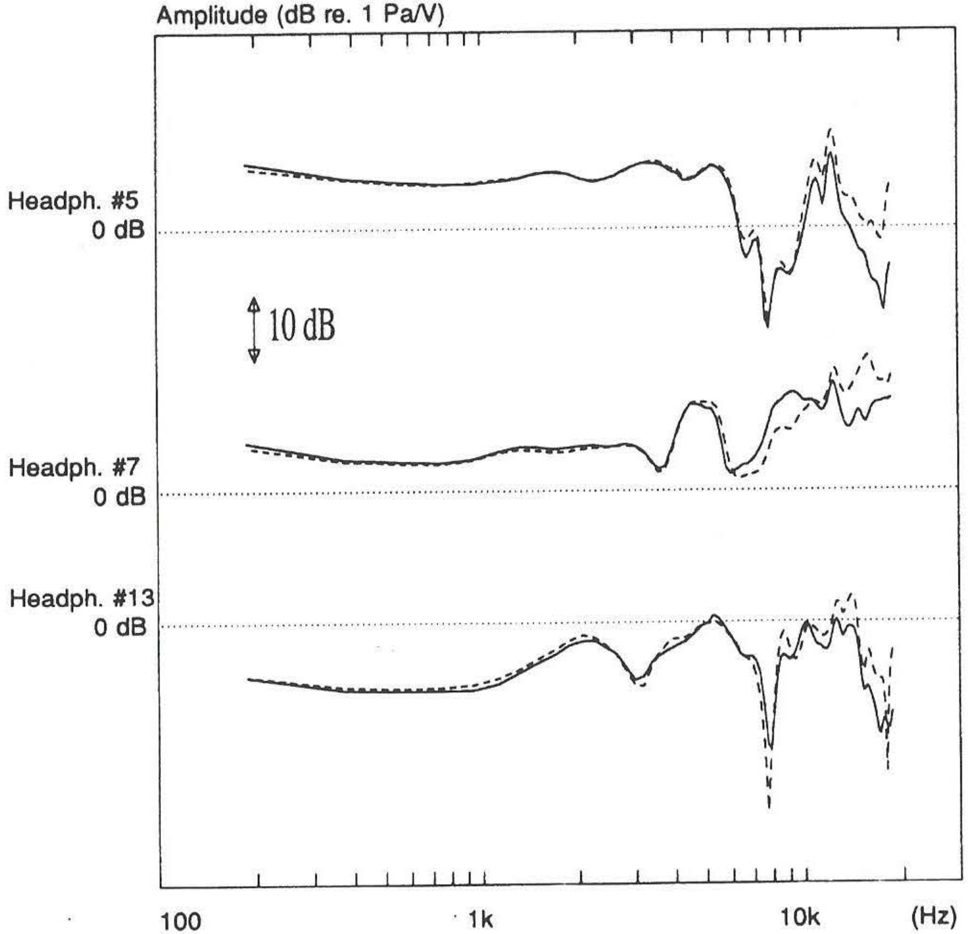


Figure 17. PTFs based on different measuring techniques for the same person, right ear for headphones numbered 5, 7 and 13. Solid lines are PTF computed on basis of measurements taken with the miniature microphone, and dashed lines are PTF computed on basis of measurements taken with the probe microphone.