Reprinted from the EBU Review - Technical No. 229 - June 1988

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The diffuse-field probe transfer function of studio-quality headphones*

There has been major progress in recent years in the standardization of sound reproduction through headphones. This progress has concerned, on the one hand, the theoretical derivation of a suitable form of headphone transfer function and, on the other hand, the development, practical testing and standardization of the corresponding measurement techniques. It has been shown in earlier articles that the frequency response of the headphone transfer function must match that of the transfer function of the outer ear, as measured in a diffuse field, if linear distortions are to be avoided when reproducing audio signals through headphones. Sound pressure measurements in the auditory canal of test listeners have proved particularly useful in the evaluation of this physically-defined headphone transfer function. For studio-quality headphones a frequency-independent "diffuse-field probe transfer function" has been defined on the basis of the measurement technique used. Admissible tolerances are given, taking account of the measurement accuracy that can be achieved and the threshold of perceptibility of changes in the coloration of sounds. Measurements using the technique on twelve high-quality headphones show that three of them meet the target specifications for the transfer function of headphones for studio use.

1. Introduction

Hi-fi headphones are now available which offer a very high standard of quality as regards audio bandwidth, non-linear distortions, maximum sound pressure, etc., and yet the price of such headphones is only a fraction of that of control-room quality loudspeakers.

Headphone reproduction offers various advantages over loudspeaker reproduction. Headphones make it possible to reproduce high volume levels — for example in order to recreate the volume generated by a symphony orchestra at a listener's position in a concert hall — without difficulty. Also, headphone reproduction is unaffected by the listening room and its acoustic properties, or by restrictions on the stereophonic listening area; several people can listen at the same time under the same conditions. Moreover, with closed headphones, even disturbing noises in the listening area can be attenuated effectively. This is particularly important in poor acoustic environments such as occur in

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* Dieser Aufsatz erscheint in Deutsch unter dem Titel "Das Diffusfeldsondenübertragungsmass eines Studiokopfhörers" in Rundfunktechnische Mitteilungen, Heft 3, 1988.

outside-broadcast vans. The greater sensitivity as regards the detection of interfering noises during sound recording operations, compared to the use of loudspeakers, merits particular consideration.

Despite these advantages, headphones are only rarely used when making stereophonic recordings. One key reason for this is the phenomenon of "in-the-head localization" [1] that occurs when listening on headphones. In effect, the sound stimulus is perceived as coming from within the listener's head and, because of the inadequate spatial projection, the evaluation of certain features of a stereophonic production (sound balance between different instruments or groups of instruments, and spatial projection) is done almost exclusively with loudspeakers. Another reason for the rejection of headphones is undoubtedly the fact that it is frequently found unpleasant to wear them for long periods.

If headphone and loudspeaker reproduction is compared in terms of sound pattern reproducibility, loudspeakers are severely disadvantaged by the influence of their physical environment. When a given headphone is used in different surroundings a reproducible sound pattern is assured; this is not the case when the same loudspeaker is used in different listening rooms, or when the loudspeakers are arranged differently in the same room. Given adequate standardization of the headphone, the goal of **reproducibility** would be achieved, but with corresponding standardization of a loudspeaker it would not. Sufficient standardization of the complete monitoring environment of **loudspeaker plus listening room**, and more particularly, monitoring loudspeaker and control room, has not yet been achieved [2, 3, 4, 5, 6]. For this reason, investigations are under way with a view to defining a reference monitoring configuration for loudspeaker reproduction [7]. Problems arise, in particular, from the interaction between loudspeakers and the listening room and the central problem is to establish if, and how, **neutral** reproduction through loudspeakers can be defined.

Similarly, the standardization of headphones, as matters stand at present, remains insufficient to the extent that it cannot be used as the basis for the definition of a reference headphone reproduction. The standards that have been established [8, 9, 10, 11, 12] ensure neither a uniform nor a neutral sound pattern, especially with regard to timbre. However the prospects for establishing appropriate standards are much better because the influence of the listening room does not have to be considered.

Great progress has been made in recent years in the standardization of headphone reproduction. On the one hand there has been progress concerning the theoretical derivation of a suitable reference for headphone reproduction by means of mathematical modelling [13] and, on the other hand, we have seen the development of appropriate measurement techniques and their practical testing and standardization.

This work, which has been widely reported [14, 15, 16, 17, 18, 19, 20] may be regarded as complete. An important result is the draft text of a preliminary standard, DIN 45619, Part 3 [21], prepared by a group of headphone experts following extensive measurements [19]. This draft text standardizes the technique used to determine the transfer function of headphones by sound pressure measurements using a probe microphone in the auditory canal of the listener.

It should be noted that the draft text deals exclusively with the physical features of the transfer function measurement technique, and it does not make any statements relating to the standardization of the frequency-dependency of the transfer function curve or the permissible tolerances. In this respect it corresponds to standard DIN 45619 Parts 1 and 2 [10, 11] and with IEC Publication 268-7 [8], although these use the method of loudness comparison, rather than that of sound pressure measurement within the auditory canal, as a means of measuring the headphone transfer characteristic.

The new measurement technique serving as the basis in [18] for defining the transfer function of studio headphones offers the following advantages over the conventional techniques:

- Psychoacoustic effects which influence the results obtained with loudness comparisons [17, 18, 20, 23, 24] are avoided. In contrast to the "loudness-comparison" transfer function of a headphone, the "sound pressure" transfer function is comparable with the corresponding outer ear transfer function.
- In principle, the sound-pressure transfer function of the headphone can be reproduced on a headphone test-jig (artificial head) which simulates the physical conditions that occur when a headphone is coupled to a human head [33].
- The measurement procedure takes less time, for a given number of listeners.
- There are no difficulties in measuring the transfer function at frequencies below 100 Hz.

The transfer function referred to above as the "sound-pressure" type, and determined in accordance with DIN 45619, Part 3, is called the "probe transfer function". Correspondingly, the transfer function measured in accordance with DIN 45619, Part 1, could be called the "loudness transfer function".

The present article will be concerned essentially with the "diffuse-field probe transfer function" (DFPTF) which is pertinent to the examination of studio headphones, and which is measured in accordance with DIN 45619, Part 3, in a diffuse sound-field. Other important quality parameters such as distortion or the subjective evaluation of user comfort will not be discussed. After an explanation of the standardized measurement technique used for determining the DFPTF of headphones, the tolerance limits applicable to the standardization of the frequency-independent DFPTF of studio headphones will be derived. This will be followed by the results of measurements on twelve high-quality headphones, using the methods described, and these will be discussed in the context of the derived criteria. The measurement results will give an indication of which of the headphones tested are suitable for use in a recording studio.

2. Studio headphone transfer function

2.1. Theory — requirement for a frequency-independent diffuse-field probe transfer function

The free-field transfer function by loudness comparison with a progressive sound wave which has been standardized in DIN 45619, Part 1, and in IEC Publication 268-7 [8, 10] has long formed the basis for evaluating headphones. Regardless of the use to be made of a headphone, a free-field transfer function has been called for which is as independent as possible of the frequency [9, 12]. In the psychoacoustic domain this is needed in audio experiments in order to generate the same hearing sensations as would be generated by a homogeneous sound field [33] (simulation of free-field conditions). In electroacoustics, a frequency-independent free-field transfer function has been called for, serving to obtain the same sound impression in the reproduction of stereophonic recordings [34] as that obtained when using monitoring loudspeakers in the studio listening room.

Nevertheless, more recent theoretical studies [14] suggest that a frequency-independent DFPTF should be used rather than a frequency-independent free-field loudness transfer function when assessing headphones for use in the monitoring of stereophonic recordings if faultless reproduction of the timbre is to be obtained [15, 18]. It has been shown that neither the use of a loudspeaker in front of the listener nor a stereophonic arrangement of loudspeakers in the listening room can serve as a reference for headphone equalization, because the resulting direction-specific features of the equalization would give rise to timbre errors. The reasons for this are explained in [14, 15, 18] and will be outlined briefly below.

In natural listening, the spectral features of the perceived sounds, which are governed by the directional characteristics of the outer ear, are dealt with in such a manner in the localization process that they do not appear as a timbre characteristic. Perception of timbre is largely independent of the location of the sound source. This "inverse filtering" [14] of the outer ear transfer function within the auditory system takes place, however, only if the effect of the outer ear is detected through the generation of the ear signals and is interpreted as resulting from this effect. This is normally the case in natural hearing.

In contrast, when sound is reproduced through headphones, the outer ear transfer function is supplanted by the transfer function of the headphone. If the headphone transfer function were to simulate exactly a distinct direction-specific outer-ear transfer function (such as the free-field transfer function for **front** signals), the localization process and hence the inverse filtering would take place in the case of a monophonic signal. The perceived listening event would occur at the reference location, i.e. in **front** of the listener. As a result of the inverse filtering, the free-field transfer function of the headphone would not lead to any timbre errors. However, for various reasons, it is impossible in practice to achieve out-of-head localization by manipulation of the headphone equalization. In particular, when reproducing stereophonic signals, a direction-specific headphone equalization will generate spectral ear signal characteristics which do not match the interaural stereophonic characteristics and do not contribute to spatial perception. Consequently they are not processed by the hearing system in accordance with the principle of inverse filtering and timbre errors result [14, 18].

There is no predominant direction of sound incidence when it is reproduced through headphones. For this reason, a direction-neutral reference should be used as the basis for equalization, rather than a direction-specific reference. A headphone transfer function describing the coupling between the headphone and the input to the auditory canal [18] and which is free of linear distortions is therefore defined, in physical terms, as being such that the headphone transfer function matches the outer-ear transfer function as measured in a **direction-neutral sound field.** In such a sound field, the directional characteristics of the outer ear are just as ineffective as they are when reproducing sound through headphones, and the situation corresponds, for example, to that occurring in the diffuse sound field created in a reverberation chamber.

Thus the requirement for a frequency-independent DFPTF for headphones, which avoids timbre errors regardless of the recording technique in use, can be satisfied provided that the headphone transfer function matches that of the outer ear, as determined in a diffuse sound field. The measurement technique appropriate for this application involves the measurement of sound pressure in the auditory canal of the listener by means of a probe microphone.

2.2. Practice DFPTF measurement method

The DFPTF measurement technique has been developed on the basis of the theoretical principles outlined above. After comprehensive measurements [19], the foundations were laid for the establishment of a standard method of headphone transfer characteristic measurement using a probe. The procedure is described in the draft standard DIN 45619, Part 3 [21]. Elements essential for the determination of the DFPTF will be described below.

2.2.1. General

The measurement procedure is used for the determination of the transfer function of one earphone of a headphone set, as a function of the frequency, by the measurement of sound pressure in the auditory canal of the listener [21]. The **direct** method starts from a comparison of the sound pressures generated by the reference sound field and by the headphone. The **indirect** method uses a reference headphone which has been calibrated using the direct method, as a substitute for the sound field. Depending on the type of sound field (diffuse or free), the diffuse-field or free-field probe transfer function can be determined.

2.2.2. Instrumentation

The test instruments include both send and receive apparatus. In general, the send equipment consists of a noise generator, third-octave filters, and at least one loudspeaker or a reference headphone, and the headphone under test. A real-time third-octave analyser can also be used, this being triggered by an appropriate wideband noise signal.

The receive equipment consists of a miniature probe-mounted microphone to measure the sound pressure in the auditory canal of the listener. In the direct method a calibrated microphone with a known free-field or diffuse-field transfer function is also required, to measure the sound pressure level at the listening location.

The outputs of the electroacoustic transducers must be measured using an RMS-reading voltmeter operating with a sufficiently long integration time.

The probe microphone (referred to simply as the "probe" for the remainder of this article) must satisfy the following requirements:

a) The sound must be picked up at a point at least 4 mm beyond the entrance to the auditory canal.

b) The probe must not occupy a cross-section in excess of 5 mm^2 in the area of the auricle and the outer 4 mm of the auditory canal.

c) The ratio of the cross-sections of the probe and the surrounding part of the auditory canal must be less than 0.6 (the average cross-sectional area of the auditory canal in adults is about 45 mm^2). The volume of the probe, including its support, must not exceed 130 mm^3.

d) There are no special constraints with regard to the free-field transfer function of the probe, but there should be no sharply-defined resonances. This condition may be regarded as being satisfied if the difference between the transfer function in any adjacent one-third octaves is less than 3 dB.

e) Care must be taken to ensure that the probe output level with the sound entrance shielded is at least 15 dB below that when it is not shielded.

f) Retaining devices must be provided to hold the probe firmly in the centre of the auditory canal. The retainer must be designed to ensure a sufficiently firm fit in auditory canals having a variety of cross-sections, whilst being easily fitted and removed.

g) It is advisable to have the probe examined by an ear specialist to verify its suitability for use by the test listeners.

2.2.3. Direct measuring method — determination of the individual diffuse-field transfer function

This measurement method is based on a comparison of voltages from a probe in the outer auditory canal of the test listener when subjected to noise signals originating, alternately, from a headphone and from a defined sound field in the listening room (in this case, the diffuse sound field in a reverberation chamber).

The test signals are generally filtered noise obtained from pink noise by means of third-octave filters having the properties set out in standard DIN 45652 [26] (centre frequencies in accordance with series b) in that document).

With wideband excitation and utilization of a third-octave analyser, care must be taken to ensure that a level difference of no more than 2 dB is measured in any third-octave band for a given headphone and listener when comparing measurements obtained with wideband and third-octave noise signals.

The sound pressure levels of the audio test signals must be chosen in such a way that the input signals to the probe amplifier are at least 10 dB above the electrical noise level of the probe itself and the acoustic noise level arising from body noises in the auditory canal. The sound pressure level at the reference point must not exceed 85 dB to prevent stress on the listener (or damage to their hearing).

The level of the headphone signal has to be set so that the probe output levels, in response to sound from the headphone and from the loudspeaker, differ by no more than 3 dB when testing with the third-octave band centred on 500 Hz.

The sound field in the reverberation chamber is considered to be sufficiently diffuse if the following criteria are met*:

- In the absence of a listener, the sound pressure level measured 15 cm in front of, behind, to the right of, to the left of, and below the reference point (defined as the position of the opening of the auditory canal), when measured with a micro-

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* These requirements are more stringent that those set out in the draft standard DIN 45619, Part 3. They are valid for the determination of the DFPTF of studio-quality headphones with minimal measurement uncertainty (see § 3.1). The requirements are usually satisfied in reverberation chambers designed for acoustic measurement purposes. If such a chamber is not available, the DFPTF of studio-quality headphones should be measured using the indirect method (§ 2.2.4).

phone with a spherical pick-up pattern, must not differ by more than 2.5 dB from the level at the reference point.

- To check the pick-up pattern, the sound pressure level at the reference point must be measured, in the absence of the listener, using a directional microphone having a directivity of at least 8 dB at frequencies above 500 Hz. With any orientation of the directional microphone, the sound pressure level in any third-octave band (having a centre frequency greater than or equal to 500 Hz) must not differ by more than 3 dB.

Test listeners, fitting of headphones

Sound pressure measurements in the auditory canal must, according to [21], be carried out on at least eight listeners. Sixteen listeners should be used when testing studio headphones, as discussed here (see § 3).

Spectacles and ear-rings should be removed before the measurements begin, and the ears should not be masked by hair. There are no particular requirements regarding the hearing capacity of the listeners, but they should not have any anomalies in the structure of the outer ear. Listeners in whom the probe cannot be fitted correctly, owing to the dimensions of the auditory canal, should be excluded from the tests. The listeners should remain as quiet as possible during the tests. Care must be taken to ensure that the headphones are worn correctly — that is, with the "left" earphone over the left ear. The listener should adjust the headphones for the most comfortable and most stable fit possible, and should himself put on and remove the headphones as required during the test sequence.

Measurement procedure

Before the measurements begin, the probe is inserted into the auditory canal of the listener. The precise point of measurement is not very critical, provided it is at least 4 mm inside the ear. The microphone cable or probe tube is fed out of the auditory canal and attached below the auricle with a sticking plaster. The probe must not move appreciably in the auditory canal when the headphones are put on or removed.

The probe voltage is measured for each noise signal while the listener is exposed to the sound field created in the reverberation chamber (first sound field measurement). Immediately afterwards, the listener puts on the headphones and the probe voltage is measured for each frequency band, with the noise delivered to the ear by the headphone (first headphone measurement). After this test the listener removes the headphones, and then puts them on again. Measurements on a different type of headphone can be carried out at this stage. The test sequence concludes with a repeat of the sound field measurement (second sound field measurement).

The probe output levels for the first and second sound field measurements are compared to ensure that the probe has not shifted during the test sequence (this is essential if accurate results are to be obtained). If the difference is greater than 2.5 dB in any frequency band the entire test sequence must be repeated. If differences in excess of 2.5 dB cannot be avoided between the two test sequences, the listener should be replaced with another person.

Evaluation

The arithmetic mean of the probe output levels for the first and second sound field measurements is determined for each noise frequency band. The arithmetic means are also calculated for the levels obtained in the two series of headphone measurements. Using these mean values, the individual DFPTF $G_{\mathrm{DS\,ind}}$ (re 1 Pa/V) of a headphone is calculated for each frequency band according to the following formula:

$$G_{\mathrm{DS\,ind}} \text{ (re 1 Pa/V)} = 20 \lg \frac{U_{\mathrm{SK}}}{U_{\mathrm{SD}}} \text{ dB} + L_{\mathrm{D}} - 94 \text{ dB} - 20 \lg \frac{U_{\mathrm{K}}}{U_{\mathrm{O}}} \text{ dB} \quad (1)$$

where $G_{\mathrm{DS\,ind}}$ diffuse-field probe transfer function of the headphone

U_{SK} RMS probe voltage when exposed to sound from the headphone

U_{SD} RMS probe voltage when exposed to the diffuse field

U_{K} RMS signal voltage applied to the headphone

U_{O} equals 1 volt

L_{D} sound pressure level at the reference point in the diffuse field.

2.2.4. *Indirect measurement method — determination of the individual diffuse-field transfer function*

If the DFPTF of a headphone has been determined according to the direct measurement method described above, this can subsequently be used as the reference instead of the diffuse sound field. The general measurement procedure is the same.

It should be noted that when using the indirect method, any inaccuracies in the measurement of the DFPTF of the reference headphone will be added to errors in the measurement using the indirect method. The transfer function of the reference headphone must therefore be determined using at least 16 test listeners [21].

Evaluation

After the mean probe voltage has been found for the first and second sets of measurements with the reference headphone, and after the two series of measurements on the headphone under test have been taken, the individual DFPTS ($G_{\mathrm{DS\,ind}}$) of the headphone is computed, for each frequency band, according to the following formula which takes account of the signal voltages applied to both the reference and tested headphones, and the DFPTF of the reference headphones:

$$G_{\mathrm{DS\,ind}} \text{ (re 1 Pa/V)} =$$
$$G_{\mathrm{DB}} + 20 \lg \frac{U_{\mathrm{B}}}{U_{\mathrm{K}}} \text{ dB} - 20 \lg \frac{U_{\mathrm{SB}}}{U_{\mathrm{SK}}} \text{ dB} \qquad (2)$$

where $G_{\mathrm{DB\,ind}}$ diffuse-field probe transfer function of the reference headphone

U_{SB} RMS probe voltage when exposed to sound from the reference headphone

U_{B} RMS signal voltage applied to the reference headphone.

Other values, as in equation (1).

2.2.5. Determination of the DFPTF of a headphone

For each frequency band, the arithmetic mean and the standard deviation are determined from the individual DFPTF values. The mean value is the DFPTF G_{DS} of the headphone being tested, for the frequency band under consideration.

3. DFPTF performance requirements of studio headphones

It has been shown in § 2.1 that the transfer function of a studio headphone should match the DFPTF of the outer ear. This implies that the DFPTF measured as described in § 2.2, should be as independent of frequency as possible. When specifying a target performance for the frequency response of the DFPTF, a number of parameters that may influence the result need to be taken into account. These parameters will now be discussed with a view to deriving a tolerance range for the DFPTF of studio headphones.

3.1. Measurement accuracy

Any irregularities appearing during the repeated determination of the DFPTF can be traced to the various properties of the headphone and they will depend very largely on the number of test listeners. The calculation of the measurement inaccuracy, which is based on results obtained at the Institut für Rundfunktechnik (IRT, Munich) and the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig), was done according to the method proposed in [27] which is based on ISO Standard 5725 [28]. The variables known as **repeatability** and **comparability** are defined in ISO 5725 and serve to characterize the inaccuracy of psychoacoustic measurements.

The **comparability** R is important in the present study. This is the amount below which the absolute value of the difference between two individual test results, obtained under different conditions, can be expected with a given probability (for example, 95 %). The expression "different conditions" is limited in the present case to meaning "different groups of listeners", and in the following we will refer to the comparability R'.

R' is calculated as follows.

Let $\bar{a}_{\mathrm{jk}}$ denote the mean value of the individual DFPTF for n listeners in group k, for measurement j, and let $\bar{\bar{a}}_{\mathrm{k}}$ denote the mean value of all m measurements in group k. The standard deviation s_{k} for all m measurements of group k is then defined as:

$$s_{\mathrm{k}} = \sqrt{\frac{1}{m-1} \sum_{j=1}^{1} (\bar{a}_{\mathrm{jk}} - \bar{\bar{a}}_{\mathrm{k}})^2} \qquad (3)$$

The mean value of the standard deviations s_{k} for all l groups yields an estimated value for R', as follows:

$$\sigma_{\mathrm{R'}} = \frac{1}{l} \sum_{k=1}^{l} s_{\mathrm{k}} \qquad (4)$$

For 95 % probability, the comparability of measurement j for different groups of listeners, each comprising n persons, is then given by:

$$R' = 2\sqrt{2}\ \sigma_{\mathrm{R'}} \qquad (5)$$

On the basis of the IRT and PTB measurements, the values shown in *Fig. 1* are obtained for the comparability R' of the DFPTF, for various num-

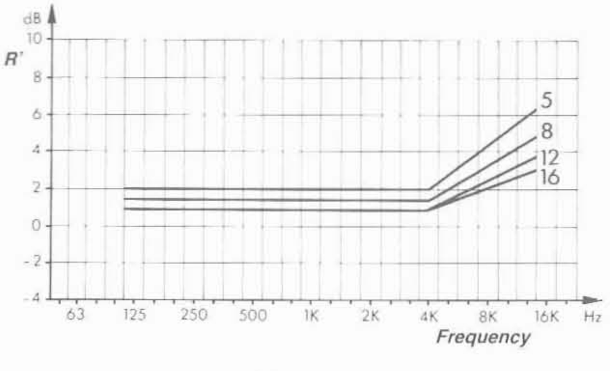


Figure 1
Comparability R' of the DFPTF as a function of the number of listeners [21].

bers of test listeners and as a function of the frequency.

The **repeatability**, which constitutes an estimate of the measurement inaccuracy in test results obtained under the same conditions (same listeners and identical test conditions) will not be discussed, other than to note that the values are very much lower, especially at medium and high frequencies.

3.2. Changes in timbre due to irregularities in the DFPTF

To establish a tolerance range for the frequency response of the DFPTF, a good starting point is the threshold of perception of fluctuations in the frequency response. The results of a relevant study are shown below [29, 30].

Pink noise was used as the test sound. It was delivered in both filtered and un-filtered forms through a headphone with diffuse-field equalization, according to [21], in an A-B-A-B sequence.

Finite impulse response (FIR) filters were used. In each of the first series of measurements the relative level of an isolated noise band one-third or a full octave wide, was raised or lowered, as a function of the centre frequency; in the second series, "structured" filtering was used, in which the levels in three adjacent frequency bands, each one-third or a full octave wide, were raised or lowered either in the sequence "up-down-up" or "down-up-down".

The reference listening level for these measurements was established using pink noise with a sound pressure level of 60 dB(A), obtained using loudspeakers in the listening room. The level of signals to the headphones was set to match the reference level by comparison of the loudness.

The loudness differences that resulted on switching between filtered noise (B) and un-filtered noise (A), because of the relative raising or lowering of the level of certain bands of the noise, were compensated on the basis of the results of comparative loudness measurements.

The listeners were required to answer the question: "Is there a noticeable timbre difference between A and B?".

The results are based on the assessments of 15 listeners and they have been analysed by evaluating the relative occurrence of "timbre difference noticed" for each test sequence or each test sound, and then calculating the median which was taken as representing the thresholds of perception.

The thresholds of perception (median values and inter-quartile ranges) established in this manner are shown in *Fig. 2*.

Above 500 Hz, the thresholds of perception for isolated relative level **increases** of one-third or a full octave band are about + 2 dB and 1 dB, respectively. For isolated relative **decreases** in level, for one-third or a full octave band, the thresholds are about − 3 dB and − 1 dB, respectively. Below 500 Hz, the hearing system is less sensitive to raised or lowered levels, as seen in *Fig. 2a* and *c*.

Where structured filtering is used, the thresholds are about ± 2 dB (one-third octave) or ± 1 dB (full octave), regardless of whether the level sequence is "up-down-up" or "down-up-down", and regardless of the frequency (*Fig. 2b* and *d*).

When examining these results, it must be borne in mind that they are based on very critical test signals and conditions which permit the detection of minute differences in timbre which would probably not be perceived in most music signals.

Furthermore, it was only possible in the study to examine the influences of frequency response variations relating to increases or decreases in level in isolated frequency bands, or in specially-constructed structures of adjacent bands. The results can therefore serve only as a guide for the determination of a tolerance range for the DFPTF of headphones. The results do nevertheless give an estimate of the extent to which deviations from a flat DFPTF response can be perceived, or the extent to which deviations of the individual DFPTF values from the mean value affect the differences in timbre. Estimates of this sort will be derived in § 3.4.

3.3. Derivation of the DFPTF tolerance range for studio-quality headphones

The tolerance range for the frequency response of the DFPTF will now be derived on the basis of the data given in §§ 3.1 and 3.2.

First, it will be assumed that, in common with other items of audio equipment, greater demands are made on the quality of recording studio headphones than would be made on ordinary "hi-fi" headphones. To ensure that measurement inaccuracies are minimized when determining the DFPTF, it is proposed that 16 listeners should be involved, rather than 8 as specified in the draft standard [21]. The proposed tolerance mask for the DFPTF (G_{DS}) frequency response shown in *Fig. 3* is based on the predicted measurement inaccuracy (§ 3.1 and curve a) in *Fig. 1*) and the thresholds of perception (§ 3.2 and *Fig. 2*).

Optimum timbre reproduction can be expected from headphones whose DFPTF falls within the proposed mask, although slight differences in timbre may still be noticed between different types of headphones. The remaining quality differences among headphones which fit the DFPTF mask will be due to other factors such as non-linearity distortions, group-delay distortions or poor matching of the two earphones of a headphone set.

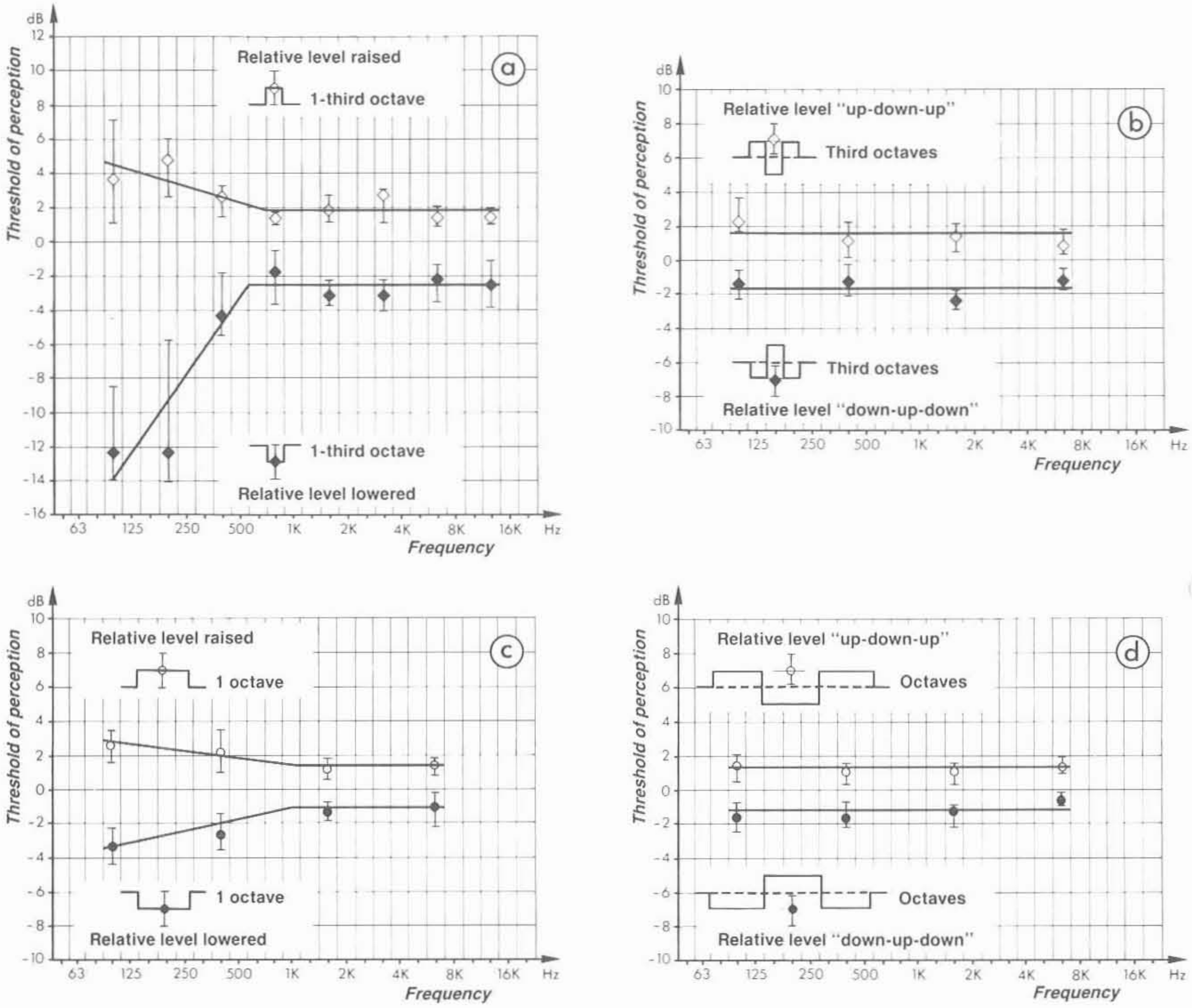


Figure 2
Threshold of perception (median, upper and lower quartiles) as a function of centre frequency.
a) Relative raising or lowering of an isolated one-third octave band.
b) Structured changes of relative level of adjacent one-third octave bands: "up-down-up" or "down-up-down".
c) As a), but with level changes in a one-octave band.
d) As b), but with level changes in adjacent one-octave bands.

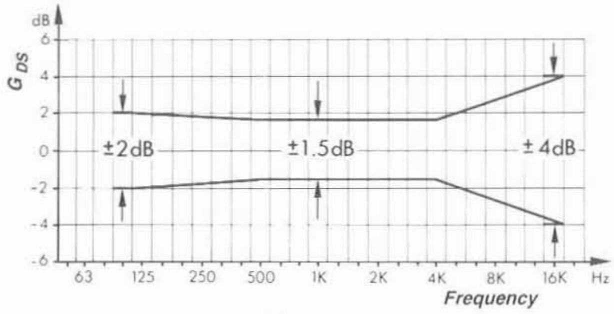


Figure 3
Proposed tolerance mask for the diffuse-field probe transfer function (G_{DS}) of studio headphones, relative to the average G_{DS} for the frequency range from 100 Hz to 16 kHz.

3.4. Mean and individual DFPTF

In principle, the equalization of a headphone can be regarded as optimum if carried out on an individual basis, i.e. when the properties of the user's outer ear are taken into account. Such equalization nonetheless requires extensive technical support and is therefore costly. It cannot be considered for a mass-produced article.

The question therefore arises concerning the differences that must be expected between an individual listener's optimum DFPTF and a mean DFPTF corresponding to a mass-produced headphone.

Referring to ISO 5725 [28], the comparability R'' may be calculated as a measure of the differences mentioned above. As noted in § 3.1, the comparability R is the amount below which the absolute value of the difference between two test results, obtained under different conditions, can be expected with a given probability (such as 95 %).

In the present case, "different conditions" is taken to mean the differences between the (various) individual measurement results and the mean value. R'' is calculated in the same way as R' (see § 3.1). First the difference between the individual DFPTF and the mean DFPTF for m listeners is calculated for each listener j of the measurement k, and then the standard deviation s_k of the measurement k is calculated. The mean value of several measurements results in an estimate of $\sigma_{R''}$. The comparability R'' for 95 % probability is then found as shown in equation (5).

The calculations have been done for $m = 8$ listeners and 3 ($k = 1,2,3$) headphones (two of open construction and one closed). The results are shown in *Fig. 4*, where it is seen that the comparability R'' fits approximately within the DFPTF tolerance mask derived in § 3. Assuming the mean DFPTF to be frequency-independent, it follows that the scatter range of the individual DFPTFs covers roughly the tolerance range of the DFPTF for studio headphones. Accordingly, there is a 95 % probability that individual equalization would not lead to any noticeable improvement.

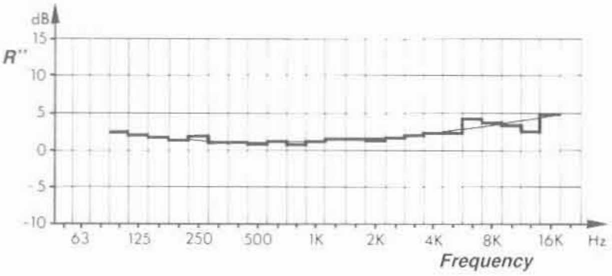


Figure 4
Comparability R'' of mean and individual DFPTFs.

To illustrate the differences between the individual DFPTFs and the mean value, the measurement results for three of the listeners and three of the headphones are shown in *Fig. 5*.

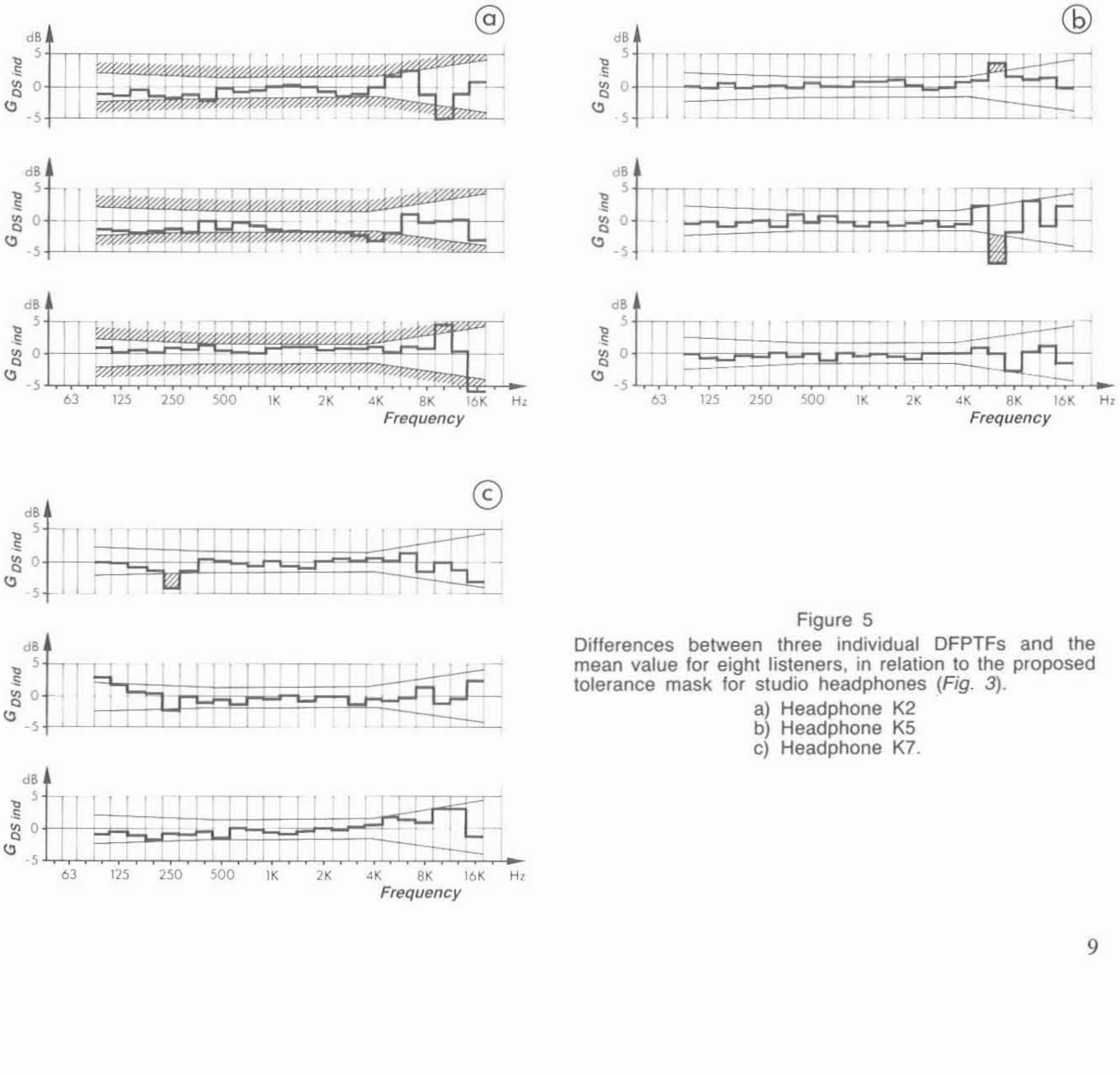


Figure 5
Differences between three individual DFPTFs and the mean value for eight listeners, in relation to the proposed tolerance mask for studio headphones (*Fig. 3*).

a) Headphone K2
b) Headphone K5
c) Headphone K7.

4. Measurement of the DFPTF of 12 headphones

DFPTF measurements have been made on twelve headphones using the method described in § 2. The headphones were selected after consultation with the manufacturers who were invited to propose high-quality models from their product lines. One headphone of each model selected was made available by the manufacturer and another was procured through normal retail channels so that comparative measurements could be made.

4.1. Execution of the measurements

The DFPTFs of five of the headphones were measured using the direct method and the other seven were subjected to the indirect measurement method. One headphone whose DFPTF had been determined using the direct method (and with 16 listeners) was used as the reference for the indirect method. The measurement arrangements for both methods are depicted in *Fig. 6.*

The tested headphones will be denoted by K1, K2, ... K12. Data on each type, taken from the manufacturers' specifications, are given in the *Appendix.*

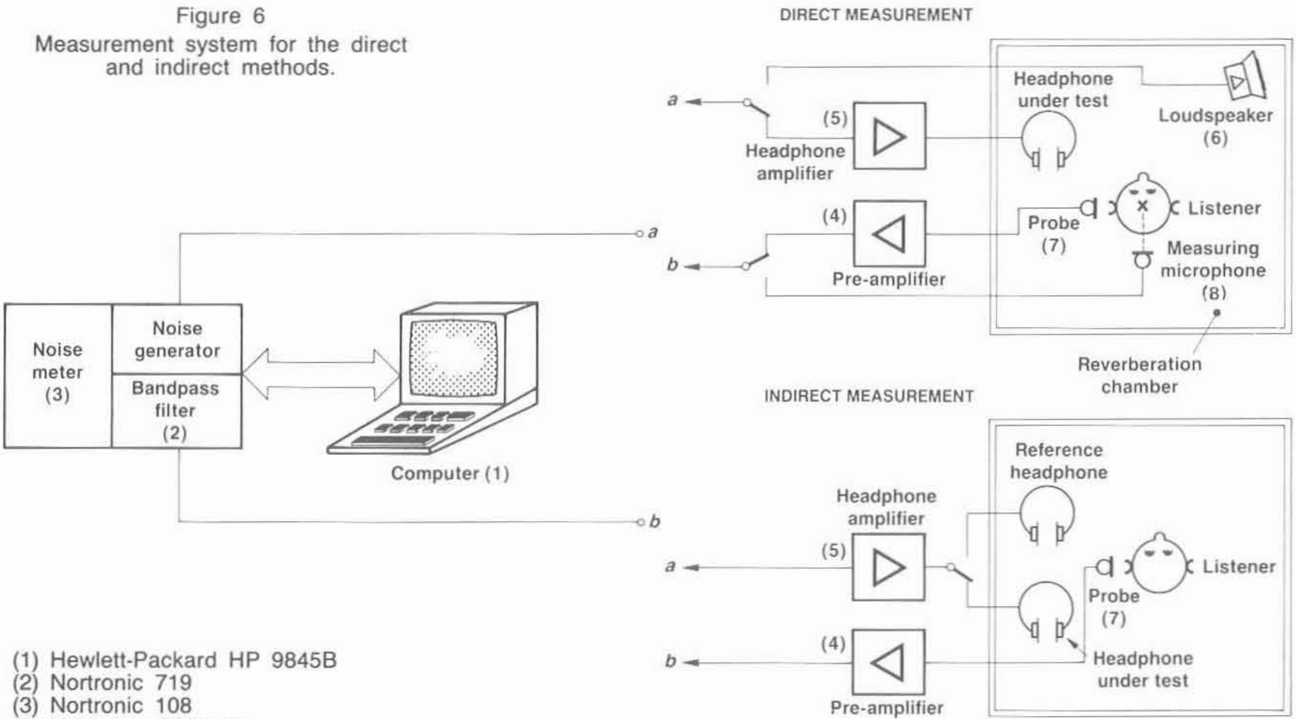
In addition to the DFPTF measurements, comparative measurements were carried out on each type of headphone using a special coupler in order to determine the difference between the DFPTFs of each earphone of a pair and between the corresponding earphones of the two headphones that were available of each model.

The coupler was built at the IRT and consists of two flat plates set up 17 cm apart, thus corresponding to the distance between the listeners' ears. The headphone was fitted onto the plates, as it would be with a human listener, and measurements were taken with a 1/2'' measuring microphone (Brüel and Kjaer 4134) mounted in one of the plates, centrally positioned with respect to the earphones. This coupler is of course only suitable for comparing earphones of the same type.

4.2. Presentation of results

The measurement results obtained from the twelve tested headphones are presented below. The mean values of the DFPTF (G_{DS}) and the standard deviations are shown in part a) of each section of *Fig. 9* superimposed over the tolerance mask that was derived in § 3. In all cases the results are those

Figure 6
Measurement system for the direct and indirect methods.



(1) Hewlett-Packard HP 9845B
(2) Nortronic 719
(3) Nortronic 108
(4) Neumann PMV 70
(5) Klein und Hummel KV 20 (or special type for electrostatic headphones)
(6) Klein und Hummel 092
(7) Beyer MCE 511
(8) Brüel & Kjaer 4145.

for just one earphone (left side). The measurements were taken in one-third octave bands, as required in [26], over the frequency range 100 Hz to 16 kHz.

In principle it is possible to measure the DFPTF below 100 Hz, and since the outer ear (including the torso, head and auricle) of an individual person has no influence at such frequencies it can in fact be measured with the probe without the need for a reference sound field, provided that the probe transfer function in this frequency range is known. However, this was not known for the probe used in the tests (*Fig. 7*), so the DFPTF could not be measured below 100 Hz.

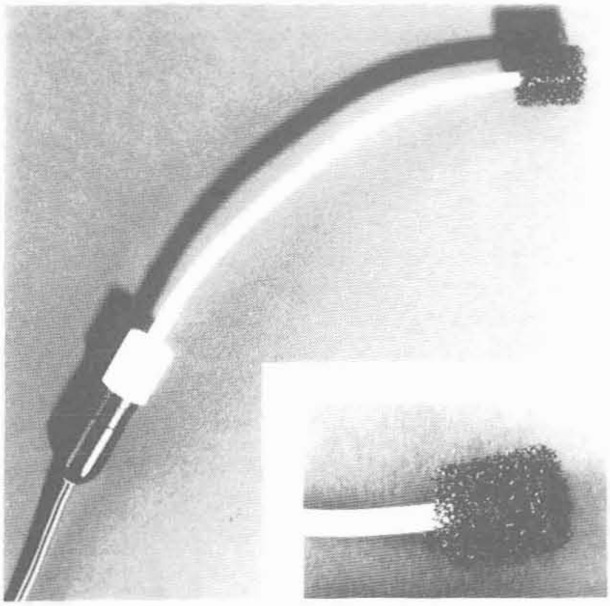


Figure 7
The miniature probe microphone and its support.

An example of the test results is given in *Fig. 8*, where the upper part shows the mean DFPTF for headphone K2 together with the eight individual DFPTFs and the lower part shows the standard deviation, calculated from the individual DFPTFs. These results correspond to the definitions set out in § 2.

The importance of the distinction made between the mean and individual DFPTFs should be emphasized again at this point. The presentation of the results in *Fig. 8* might suggest that major differences between the mean and individual values, and accompanying timbre errors, will occur if the mean DFPTF is assumed to be frequency-independent. It has been shown in § 3.4, however, that only minor timbre errors, if any, should generally be expected as a result of differences in the characteristics of the outer ears of individual listeners.

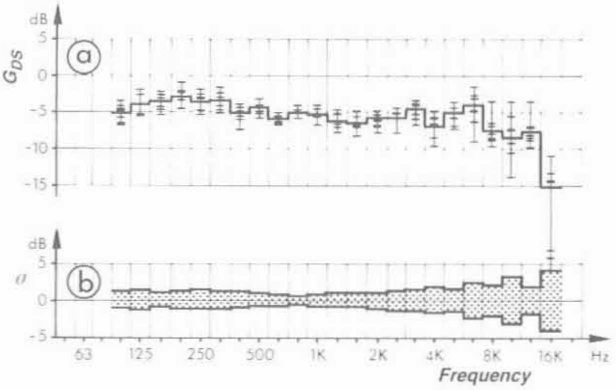


Figure 8
a) Mean value of the DFPTF of headphone K2, and 8 individual measurement results.
b) Standard deviation σ.

The reference headphone (K1) was measured using 16 listeners, as proposed in [21]. The mean values for eight listeners were determined for the eleven others. Headphones K1 to K5 were measured using the direct method, and K6 to K12 using the indirect method.

The mean and standard deviations of all twelve headphones are plotted in part a) of each section of *Fig. 9*. The differences in transfer function between the left and right earphones of each headphone, determined using the special coupler described earlier, are plotted in part b). Finally, part c) of each section shows the differences in transfer function between the corresponding earphones of the two headphones of each model that were available.

The results in parts b) and c) of *Fig. 9* are for the average of three coupler measurements, established with a standard deviation below 1 dB. The shaded tolerance mask in part b) corresponds to standard DIN 45500, Part 10 [12] over the frequency range 250 Hz to 8 kHz.

4.3. Comparison of the direct and indirect methods

The DFPTFs of headphones K2 and K5 were determined using both the direct and the indirect methods, as described in § 2.

The differences between the results are shown in *Fig. 10*, where it may be seen that the differences are within the proposed tolerance mask for studio headphones.

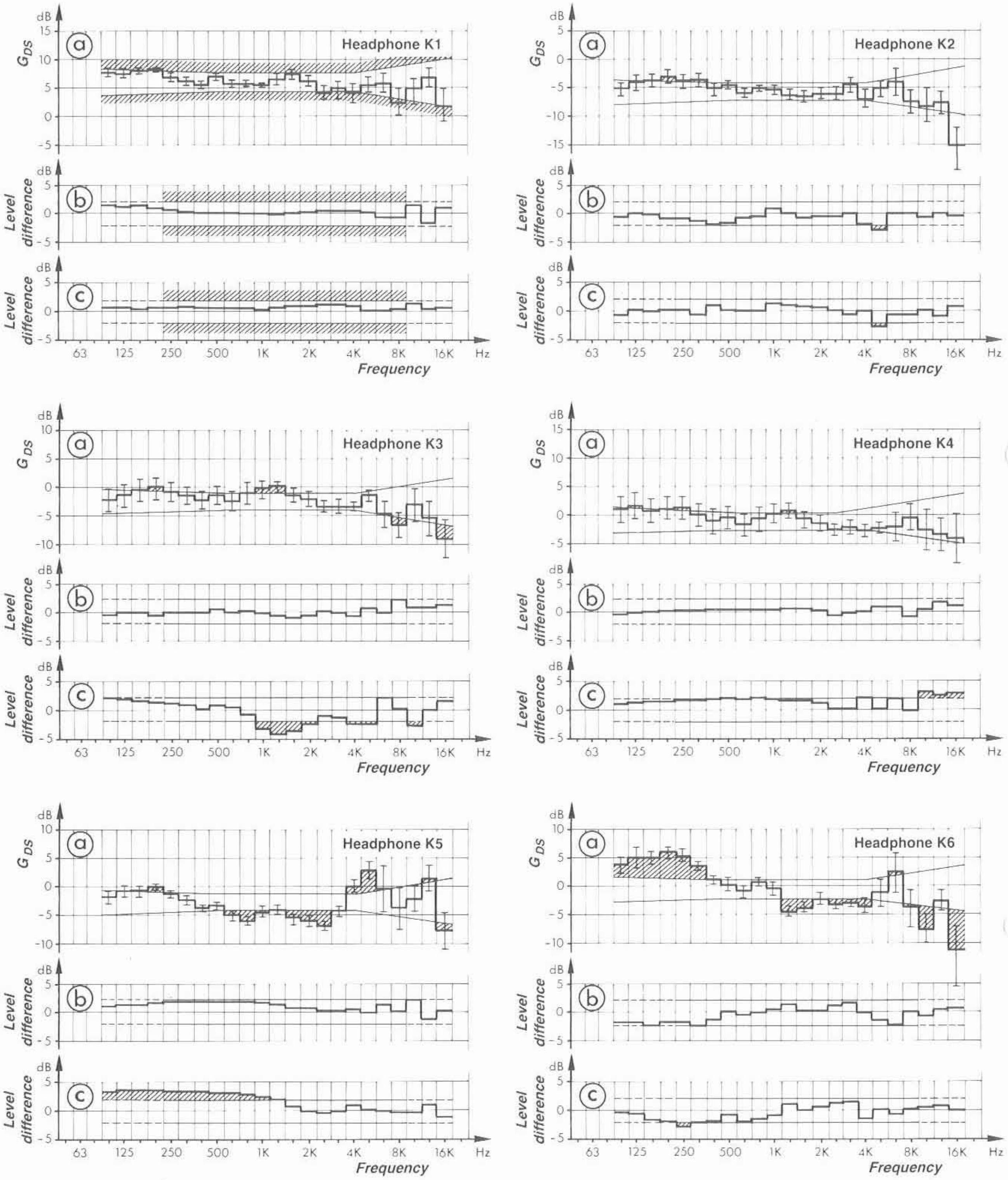


Figure 9

Notes

(i) Headphone K1 was the reference for the tests using the indirect method.
(ii) 16 listeners for K1, 8 listeners for K2 to K11.
(iii) Direct method used for K1 to K5, indirect method for K6 to K12.

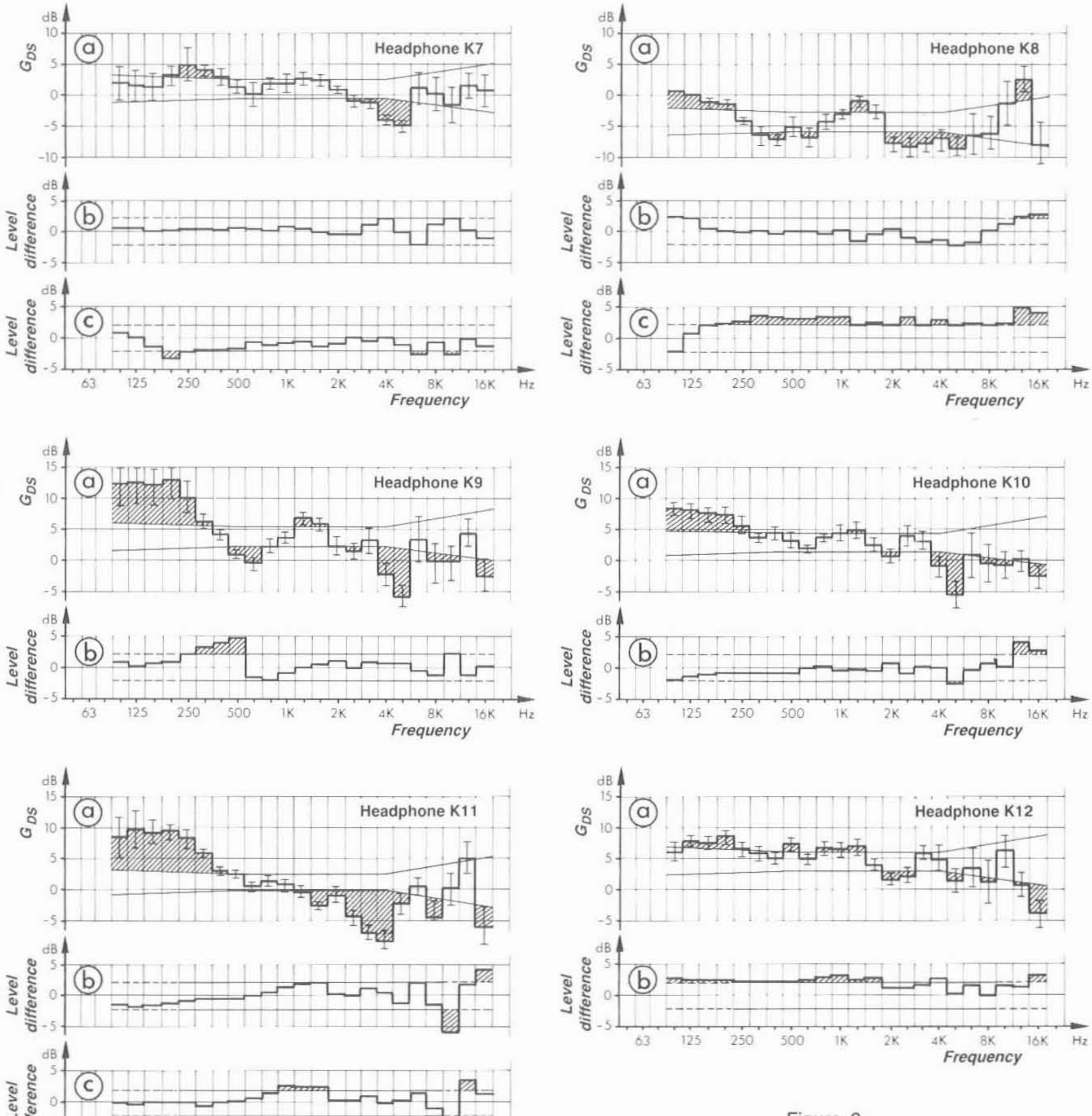


Figure 9
Measurement results on the 12 headphones subjected to tests.

a) Mean value and standard deviation of G_{DS} for the left earphone of the headphone, shown against the tolerance mask of *Fig. 5.*

b) Difference between the transfer functions of the left and right earphones of the headphone (right-hand minus left-hand), shown against the tolerance mask given in [12].

c) Difference between the transfer functions of two headphones of the same type (left-hand earphone of one headphone minus right-hand earphone of the other), shown against the tolerance mask given in [12].

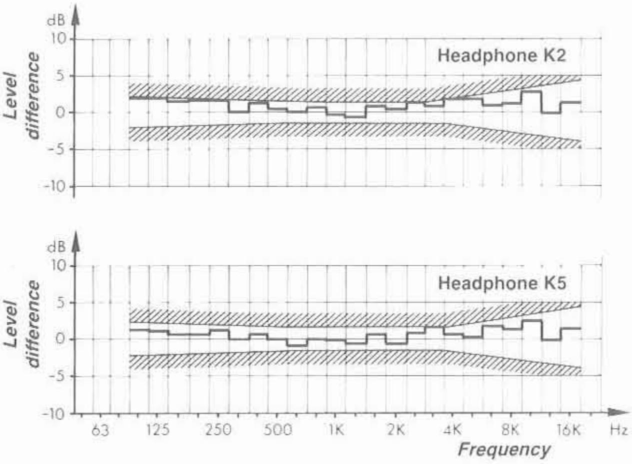


Figure 10
Difference between the DFPTF of headphones K2 and K5 when using the direct and indirect methods, shown against the tolerance mask of *Fig. 3*.

4.4 Evaluation of the results*

Of the twelve headphones tested, only K1 and K4 (and K2, if the result at 16 kHz is neglected) meet the requirements for use as studio headphones. With certain reservations, K3 is also suitable because its DFPTF exceeds the proposed tolerance mask only very slightly. All the other headphones produce timbre errors in line with the frequency-dependent nature of their DFPTFs, and are therefore not suitable for studio use.

According to information received from the manufacturers, achieving proper equalization is not a problem. Diffuse-field equalization can be established either acoustically, by design modifications, or electrically through the use of an equalizing network.

As regards the differences between the DFPTFs of the two earphones of a given headphone, it may be seen that a high standard is achieved, with just a few exceptions. It should be noted that, to meet the requirements for studio headphones, the tolerance mask ought to be extended to cover the full frequency range from 100 Hz to 16 kHz, in accordance with [12]. The differences shown assume that the headphones or earphones being compared are effectively within the proposed tolerance mask for the DFPTF of studio headphones, and that the DFPTF of the reference earphone is to be frequency-independent.

5. Conclusions

The measurement technique that has been described for determining the DFPTF of studio headphones is such that it ensures that linear distortions occurring during the reproduction of stereophonic signals through the headphones are detected with sufficient accuracy. These distortions can be avoided if the stated requirements regarding the properties of the reference sound field and the number of test listeners are complied with, and if a frequency-independent DFPTF within the specified tolerance range is established.

The frequency response of the DFPTF, measured according to the method set out in this article, is therefore suited for use as a quality parameter when headphones are used for monitoring. Owing to differences in listening rooms and control rooms, it has not yet been possible to achieve reproductibility of the sound pattern when loudspeakers are used.

In conclusion, it should be emphasized again that the performance-testing requirements that have been described relate specifically to studio headphones. Less stringent measurement techniques are laid down in the draft of standard DIN 45619, Part 3, in respect of the diffuse nature of the reference sound field and the number of test listeners. The measurement accuracy which can be achieved with data obtained in accordance with the above-mentioned draft standard is insufficient for assessing the transfer function of studio headphones. Also, the tolerances allowed in standard DIN 45500, Part 10 [12] and IEC Publication 581-10 [9] are too great for a frequency-independent headphone transfer function, and it is suggested that the tolerances derived in the present article should be standardized nationally and internationally, for example in the form of an ARD standard or a CCIR Recommendation. These same procedures should be considered as an essential prerequisite for subjective sound quality assessments (for example, according to CCIR Recommendation 562-3 [31]) so that uniform listening conditions prevail, leading to comparable results.

The measurement results reported in *Fig. 9* show that the frequency responses of the headphone transfer functions vary widely, in spite of the existence of standards. Headphones K1, K2, K3, K4, K5 and K7 are described by their manufacturers as being "diffuse-field equalized". The results show, too, that manufacturers are able to make products which perform according to the proposed specifications. The technical facilities needed for execution of the measurement technique can be minimized by using a suitable reference headphone rather than a reference sound field. Furthermore, it is to be expected that suitable forms of artificial head [32], able to imitate the coupling between the headphone and the human ear with sufficient accuracy, will be used in the future, rather than human listeners.

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* The publication of the author's findings in the EBU Review in no way reflects an official opinion of the European Broadcasting Union regarding the suitability or otherwise, for any specific application, of any of the products mentioned. (Editor.)

APPENDIX

Headphone data

The data given below for the headphones examined in the tests described here are extracted from the manufacturers' data sheets.

	K 1	K 2	K 3	K 4	K 5	K 6	K 7	K 8	K 9	K 10	K 11	K 12
Transducer principle a) electrodynamic b) electrostatic	b	a	a	a	a	a	a	b	a	a	a two-way system	b
Acoustic mode of operation a) open, semi-open b) closed	a	a	a	a	a	a	b	a	b	a	b	a
Rated sound pressure level (DIN 45580) dB	—	90	94	96	94	—	96	—	96	94	94	—
Form of coupling between ear-piece and ear a) circumaural b) special design	a	a	a	a	a	a	a	b	a	a	a	a
Contact pressure N	—	3.5	1.5	2	—	2.5	3.5	—	—	—	4	—
Weight g	325	240	210	230	250	180	250	—	245	245	260	390

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