On the Standardization of the Frequency Response of High-Quality Studio Headphones*

GÜNTHER THEILE

Institut für Rundfunktechnik GmbH (IRT), Munich, West Germany

The use of headphones in the studio is appropriate under certain circumstances. Addressing the problem of defining and measuring the frequency response of high-quality studio headphones, it is argued that the current headphone standards are unsuitable for this purpose. A study of recent work on the properties of spatial hearing shows that the free-field equalization applied to headphones cannot produce good results. A more satisfactory equalization is obtained by reference to the diffuse field defined on the basis of the average value of the transfer functions of the outer ear in different directions. Further it is shown that measuring methods based on a comparison of loudness produce wrong results and that, instead, purely physical measurements should be taken as a basis. The diffuse-field response of several new studio headphones has been measured in accordance with an IRT proposal (auditory canal probe microphone technique). The diffuse-field frequency responses are compared with results obtained with a special dummy-head technique. Subjective assessment experiments carried out using commercially available headphones are reported.

0 INTRODUCTION

Recently Toole [1] presented a study on the acoustics and psychoacoustics of headphones. His close examination of stereophonic headphones and headphone listening reveals some serious problems in achieving high-quality headphone reproduction. The main problems he reports are, in summary, as follows [1]:

1) The design and evaluation of stereophonic headphones are at present based on imperfect measurement techniques and uncertain performance objectives. While there are some indications of how improvements can be made, the precise solutions are not yet obvious and are complicated by the substantial physical variations among individual ears.

2) There are some fundamental issues related to the purposes of headphone reproduction. For example, from the point of view of spatial fidelity, the recording methods best adapted to headphone reproduction are not widely used, and the popular stereophonic recording methods are not well adapted to headphone listening. From the point of view of sound quality, headphones optimized for conventional stereo recordings will be incorrect for dummy-head recordings, and vice versa.

3) Some headphone designs can reduce the variation in the acoustical coupling to individual ears, but there remains the problem of choosing the optimum correct performance. This optimum performance must be defined from measurements made on real ears. By the same token, headphones should be measured on real ears or on a device that in the essential anatomical and acoustical respects closely resembles real ears.

These questions have been examined at the Institute of Broadcast Technique (IRT) in Munich during the past 3 years in order to prepare national and international standards for high-quality studio headphones [2]. This paper presents the most significant results of this work, addressing the current discussion on defining and measuring the "correct" frequency response of headphones.

1 REQUIREMENT OF STANDARDIZATION OF STUDIO HEADPHONES IN BROADCASTING

Headphones are relatively rarely used in studios, although they are not inferior to large commercially available monitor loudspeakers as regards distortion, maximum sound pressure level, bandwidth, and so on.

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There are a variety of reasons for this lack of use. The main one is the phenomenon of in-head localization [3], [4], which means that in the case of conventional stereo recordings and headphone listening the auditory events appear to occur within the head. This incorrect perception of distances corresponds to a considerable loss in spatial reproduction, so that stereo productions may be evaluated more accurately using loudspeakers rather than using headphones.

Nevertheless, if these drawbacks are disregarded, headphone reproduction has advantages that are particularly appreciated by listeners. It can provide the original sound intensity without difficulty, and it is a simple means of obtaining excellent sound quality irrespective of the installation and acoustic characteristics of the listening area and its sound insulation with regard to the surroundings. In addition, headphones can considerably attenuate the ambient noise in the reproduction area so that the dynamic range of the program signal can in fact be achieved without any additional constraint. As a result, in many cases headphone reproduction makes more concentrated listening possible, is less likely to cause disturbance, and is therefore frequently preferred to loudspeaker reproduction by listeners.

Headphones have acquired additional importance as a result of the introduction of dummy-head stereo sound. Productions of this type have been made and broadcast by German broadcasting organizations for some 10 years. Interest in this technique has been considerable, particularly among listeners. As a result, approximately 3 years ago a specially designed studio dummy head (KU 81, Neumann) became commercially available, and it can be expected that this type of stereo transmission will be used as an alternative to conventional stereo transmission. This is yet another case where headphone listening is an important alternative to loudspeaker reproduction.

As a result, also for radio purposes, headphones should be considered important. The use of headphones is indispensable for listening to dummy-head productions, but it is also necessary for listening to other types of productions under poor conditions. Headphones are also used as a complement to loudspeaker reproduction in the case of all normal productions inasmuch as many listeners like using them.

Furthermore, the international program exchange requires sufficiently standardized listening conditions. Headphone listening conditions can in principle be defined with great accuracy and can easily be reproduced without any systematic error. The same does not hold true for listening to loudspeakers. International efforts at standardizing the acoustic and geometric characteristics of sound control rooms and listening rooms have not yet, for understandable reasons, produced an adequate level of standardization. Neither EBU Recommendation R22-1980 nor the proposals contained in CCIR Report 797-1 provide guarantees of sufficiently standardized listening conditions. There can be no expectation of major progress, in the future, in the standardization of loudspeaker reproduction, at least at the international level.

Conversely, headphone reproduction offers optimum conditions for practicable international standardization of listening conditions. Because it is independent of the geometric and acoustic properties of the listening area, standardization can be achieved with very little effort and can be accurately maintained without difficulty.

If, in the case of high-quality listening, the use of headphones is considered to be of similar importance to that of loudspeakers, the quality of sound transmission must not be assessed solely using loudspeakers. It has been shown that certain quality shortcomings are more clearly perceptible in the case of headphone reproduction than in that of loudspeaker reproduction. For example, the signal-to-noise ratio corresponding to noiseless headphone listening exceeds the value obtained using loudspeakers by about 5 dB (average value for music) and 12 dB (average value for female speech) [5]. Similar differences occur in the case of the quality losses due to clicks (caused by bit errors in digital transmission), quantizing errors, nonlinear distortions, and so on.

As regards the subjective assessment of the quality of sound transmission, CCIR Recommendation 562-1 gives important indications on the grading of quality and the choice of test program material, test persons, and test procedures. It also contains recommendations concerning the listening conditions, which apply to loudspeaker as well as headphone reproduction, depending on the category of impairment to be assessed. Only those factors that affect the spatial reproduction should be assessed by means of loudspeakers.

However, it would appear at present that headphone listening conditions have not been adequately defined. The standardization specified in IEC Publications 268-7 (1981) and 581-10 and in the standards DIN 45 619, page 1 (1975), and 45 500, page 10 (1975), fails to provide either the optimum sound neutrality or an adequate standard sound image.

2 NEW BASES FOR DEFINING AND MEASURING THE FREQUENCY RESPONSE OF STUDIO HEADPHONES

Recently, in connection with the further development of dummy-head stereo, a general solution to the problem of compatibility between various processes of sound signal production and reproduction has been found [6]. In close relation to this process, theoretical concepts referring to the function of our hearing in spatial listening are expanded and described using a localization model known as association model [7]. This provides a unified explanation of major phenomena of spatial listening, which could be used to define appropriate studio headphones.

2.1 The Association Model

The association model is based on the assumption that association phenomena constitute a basic principle of sensory stimulation perception. On that basis, auditive spatial perception fundamentally results from two separate processes. Each process occurs by means of an associatively guided pattern recognition. A momentary stimulus, derived from a sound source, initially induces a "location association" and then a "Gestalt association." The characteristic feature of this localization model resides in the two-stage processing of the stimulus. It contains not only the stage of processing that determines the localization, but also the stage that determines the Gestalt. (*Gestalt* is a term used in perception research.) Both stages must be gone through for the stimulus to achieve a form of perception. Accordingly, both processes jointly determine in every instance the properties of the auditory event.

Fig. 1 shows a block diagram of the model. The spatial transmission system in hearing consists of the outer ear, represented by transfer function M, and of the localizing stage, represented by transfer function M^{-1}, the inverse of M. The dependence of ear signals on the source location is indicated as a form of coding of spatial information M, which enables the spatial information M^{-1} to be decoded. The operation can be described as that of an adaptive filter with a transfer function M^{-1} which, as a result of associative recognition of the model, is in inverse relation to M, the transfer function of the outer ear, which in turn depends on the location of the source. Details have been described in [7]. The adaptive operation of the localization stage gives rise to two consequences with regard to the definition of optimum headphone responses. These are examined briefly below.

2.2 Objections to the Free-Field Equalization

The inverse filtering M^{-1} frees ear signals from any influence by the outer ear before the source signal reaches the Gestalt-determining stage. This means that in natural hearing, spectral features caused by the directivity of the outer ear are apprehended in such a way that they do not occur as tone color defects (Fig. 1). The association model indicates that the perception of timbre is independent of the source location. This timbre phenomenon can be verified readily, but has been described in publications only very recently [7]–[9], and it is called "invariability of timbre." The auditory system identifies the location and timbre of the sound source, and that is why timbre is not totally determined by the power spectrum of the ear signals. This fundamental attribute of spatial hearing is represented in the model by the term $M \cdot M^{-1} = 1$.

However, M^{-1} filtering only occurs when the effect of the outer ear in the formation of the ear signals is "recognized." This inverse filtering occurs normally in "natural listening," that is, when ear signals of sufficiently broad band present the corresponding outer ear features.

What happens when headphone listening is substituted for "natural listening"? Fig. 2 shows a block diagram of this situation. Using headphones, the directivity of the outer ear is ineffectual, and K is substituted for M. The location-determining stage cannot recognize any spatial information M if the microphone signal is not a dummy-head signal. (A dummy head represents a "dummy M," and one can simulate "natural listening" without linear distortions assuming the transfer function of the headphone $K = 1$.) Details have been presented in [6].

Replacing the dummy-head microphone by a conventional microphone technique, listening appears to be quite unnatural. Neither microphone nor headphone produce natural spatial information. The problem now is how to define a frequency response of K, which avoids tone color defects.

The statement "free-field equalization" seems to be correct: if the headphone would have an exact free-field transfer function M_0 (frontal sound incidence, according to current headphone standards), the location-determining stage M^{-1} would become inverse to M_0, and we would have $M_0 \cdot M^{-1} = 1$. In this case the microphone signal would arrive at the Gestalt-determining stage without linear distortion.

However, reproducing a monophonic signal, the free-field equalization $M_0 \cdot M^{-1} = 1$ is achieved only if the auditory event would arise in the median plane outside the head (more precisely at the reference point for M_0). An adequate exact equalization is not possible for mass-produced headphones. Reproducing conventional stereo signals, the free-field equalization M_0 is even theoretically wrong. The "substituted outer ear" transfer function $K = M_0$ is only relevant for frontal incidence

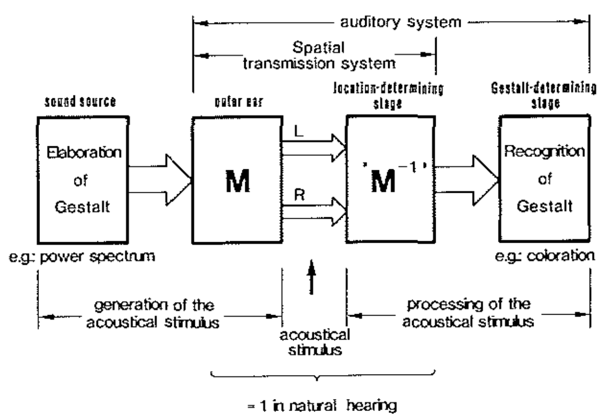

Fig. 1. Principal function of the association model.

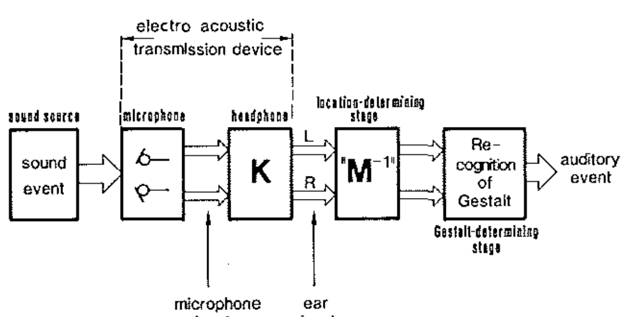

Fig. 2. Principal function of the association model. Headphone reproduction of stereophonic signals.

of sound (monophonic signals). Conventional stereo signals produce interaural level and time differences, but without adequate spectral cues. Tool [1] describes this situation: "This is simply loudspeaker stereo with the loudspeakers 'whispering' in the ears." In that case the localization process adapts to the headphones, manifesting itself as in-head localization ("phantom source in the head" [7]; it is $M^{-1} = 1$.

This means that the spectral characteristics of the ear signals caused by M_0 of the headphone intervene at the Gestalt-determining stage and not at the location-determining stage. It is $M_0 \cdot M^{-1} = M_0$; the M^{-1} inverse filtering does not occur and tone color defects result due to M_0. A free-field equalized headphone causes "linear distortions."

2.3 Requirement of the Diffuse-Field Equalization

Tone color defects consequently can be avoided only if the equalization of the headphone coupled to the auditory canal entrance is $K = 1$. Thus a transmission without linear distortions, $K \cdot M^{-1} = 1$, is achieved. In the following it is shown that the condition $K = 1$ can be obtained by means of physical measurements.

In Fig. 3 two situations of the auditory system feed with sound are considered.

In situation 1 [Fig. 3(a)], the outer ear (torso, head, pinna) operates as an acoustical antenna in a sound field, which may represent a reference sound field. $M = M(\Omega)$ is the transfer function depending on the direction Ω of incident sound. It is called transfer function of the outer ear. C is the term that does not depend on the direction of incident sound; S is the measuring point inside the ear canal (a few millimeters ahead of the eardrum).

In situation 2 [Fig. 3(b)], using a headphone, a transfer function K of the headphone is substituted for the transfer function $M(\Omega)$ of the outer ear. The term C is identical to that in Fig. 3(a) and the measuring point S is also the same.

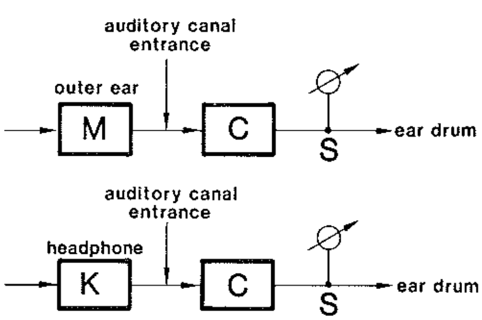

Fig. 3. Equivalent block diagram for determining the headphone transfer function related to the outer ear. $M = M(\Omega)$—transfer function of outer ear; C—transfer function, not depending on direction of incident sound; K—transfer function of headphone, coupled to auditory canal entrance.

In order to measure K, a relative measuring method is derived, using a probe microphone at the measuring point S. The sound pressures received via loudspeaker (corresponding to situation 1) and via headphone (corresponding to situation 2) are measured at point S and compared. If there is no difference, the transfer functions $M \cdot C$ and $K \cdot C$ are identical, and $K = M$.

The determination of K relative to M is necessary, because one cannot define the auditory canal entrance anatomically. Further, the influence of the probe microphone on the sound propagation in the auditory canal has to be eliminated. The probe itself as well as the position of the probe do not influence the ratio K/M, because these indeterminable terms do not differ in situations 1 and 2.

If the measuring result is $K = M$, there has to be $M = 1$ in order to keep the condition $K = 1$. What does $M = 1$ mean? $M \cdot C = M\ (\Omega) \cdot C$ is a free-field transfer function of the outer ear, depending on the direction Ω of the incident sound, which is measured at the point S in the auditory canal. It can be split into the terms $M\ (\Omega)$ and C. C is defined as independent of all directions of incident sound. Consequently the average transfer function is $\overline{M(\Omega)} = 1$. That means $M = 1$ is achieved in the case where the distribution of incident sound is completely at random.

If the transfer function of the headphone (measured at any point S in the auditory canal) is equal to the transfer function of the outer ear in the diffuse field (measured at the same point S in the auditory canal), the headphone transfer function is flat. For this reason linear distortions by headphone reproduction are physically defined and measurable. It is not necessary to define "tone color quality" because it is possible to define a flat frequency response at the auditory canal entrance.

2.4 Objections to Loudness Comparison Method

Unfortunately IEC Publication 268-7 as well as the German standard DIN 45 619 do not recommend a physical measuring method. A method of making a loudness comparison is recommended instead. Test subjects adjust the "headphone loudness" of narrow-band test signals (one-third-octave noise) by comparison with a reference sound field, which is adjusted to a constant sound pressure level (70 dB). The test subject determines then whether each frequency band received via the headphone is perceived as loud as the reference sound. If not, the voltage of the headphone is adjusted accordingly and then measured. Thus the resulting values represent the "loudness transfer function" of the headphone.

This procedure was introduced on the assumption that, irrespective of the headphone design, the same acoustic impression is achieved as with loudspeaker reproduction if the headphone produces the same loudness for each one-third octave. This assumption seems self-evident. But it has been theoretically deduced from the association model that the method of loudness comparison produces errors in determining the headphone transfer function: the loudness transfer function and the physical transfer function do not coincide. Details of this hypothesis are considered briefly in the following.

According to the association model, the effect of the outer ear on the ear signal is compensated in the localization process (see Sec. 2.1). The linear distortions caused by the directive filter constituted by the outer ear do not in principle affect tone color defects. In other words, our hearing cannot be conceived as a microphone with a fixed weighting filter; the perceptions of loudness and tone color are not completely determined by sound pressure and spectrum in the auditory canal. Our hearing is much more like a microphone combined with a variable signal circuit. This weighting circuit adapts in a complex manner and is dependent on the localization process, which is related to the formation of the event perceived [6], [7], [9].

This adapting weighting circuit, depending on the localization process, operates as a "discriminator" in order to identify the location as well as the nature of the source. Out of this processing arises the capability of the auditory system to interpret certain characters of sound events either as a specific spatial attribute or as a specific attribute of the nature of the source. This capability is essential to the perception of space, but it is not helpful in the case of loudness comparison measurings because loudness is also a spatial attribute (such as the distance of the source) as well as an attribute of the nature of the source (such as the power of the source), see Sec. 2.6.

The disturbing effect can be explained by means of an example well known in visual perception. Three equally large figures are perceived as equal in size, as shown in Fig. 4(a). Completing the drawing by perspective [Fig. 4(b)] and achieving different perceived distances of the figures, the figures appear not to be equal in size. It is difficult to recognize the size of the figures independently of the perceived distance. In other words, it is difficult to separate perceived size and distance. This effect illustrates that in order to compare sizes it is necessary to guarantee perceived equal distances.

With regard to hearing and following the described model, an equivalent relationship between localization and identification has to be presumed.

2.5 The SLD Effect

Investigations according to this hypothesis have been carried out recently [2], [10]–[11], using the loudness comparison method for headphones described. The following relevant results were obtained.

Rudmose [13] postulated a so-called "source location effect, carrying out experiments on the "missing 6-dB effect." He found that approximately 4 dB more sound level at the eardrum was sometimes required when the near loudspeaker was the source than when the far loudspeaker was the source (100-Hz test signal).

Rudmose describes the far and near loudspeaker source problem [13]: "Listeners who demonstrate this phenomenon evidently perceive the distant source as having a 'large acoustic size,' whereas the near source is perceived as much 'smaller'; consequently the smaller source must be 'stronger' (produce more sound pressure) to equal the loudness of the larger source."

Similar sound level loudness divergence (SLD) occurs in particular in standardized headphone measurements. Fig. 5 shows a number of differences in the free-field transfer functions of various headphones (loudness measurements versus those made using probes, from publications and own measurements), including the different averages. This shows that the SLD effect is frequency dependent. It can probably be avoided if the location of the sound sources is fixed during the loudness comparison. This would only be successful with discrete tones, a fixed head, a listener who is unaware of the source location, and, finally, the prevention of vibrational energy transfer (from the loudspeaker to the listener).

However, such requirements are not applicable for a headphone standard. Only for low frequencies have loudness measurements under these conditions produced the same results as measurements using probes [13].

The SLD effect is incompatible with the statement of Robinson et al. [14] that "loudness is determined

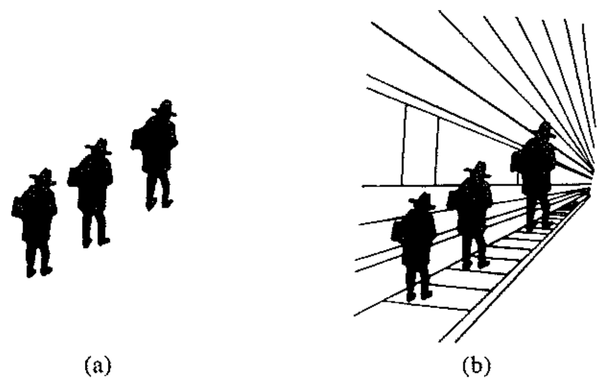

Fig. 4. Figures of equal size. The perception of size depends on the perception of distance.

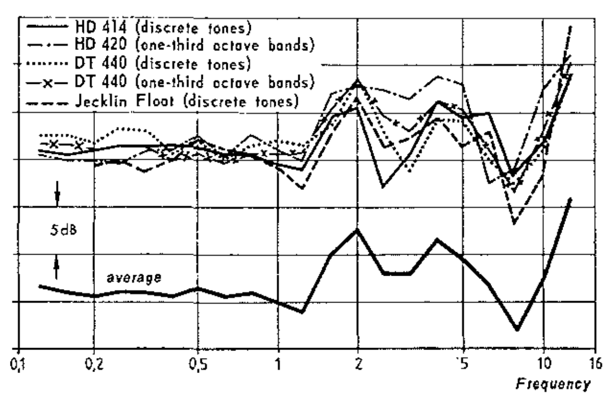

Fig. 5. SLD effect. Differences of free-field transfer functions for various headphones (loudness comparison measurement minus probe microphone measurement).

only by sound pressure at the ears," which seems to be incorrect in this general form. For example, our own experiments and similar work carried out by Mathers and Landsdowne [15] show that differences are found in the sound pressure levels measured in the auditory canal in the range of 7.5–14 dB between loudspeaker and headphone reproduction, while the test subject considers both to have equal loudness. Headphone reproduction requires more sound level in the auditory canal than equal loudspeaker reproduction. Similar effects are observable in headphone reproduction when switching from dummy-head signals to stereophonic signals.

Furthermore, the relation between sound pressure levels of narrow bands of noise in a diffuse field and in a frontally incident free field for equal loudness is described in ISO 454 [Fig. 6(a)]. This curve is obtained by loudness comparison. A different curve is obtained by probe measurement [Fig. 6(b)]. The difference between curves (a) and (b) is the SLD curve, which occurs whenever auditory events with differing locations are being compared.

Recently Sahr [10] examined measuring methods for headphones. His results are summarized in Fig. 7. Comparing the loudness transfer functions with the probe transfer functions of the headphone (HD 430), the SLD effect can be observed similarly to Fig. 5, but in the diffuse field it is less distinct than in the free field.

Further experiments have been carried out recently in order to examine the SLD effect carefully in the free field [11] as well as in the diffuse field [12]. First results show that the SLD effect occurs when measuring headphones using the loudness comparison method according to IEC Publication 268-7 or DIN 45 619-1.

So far the results agree with the theoretically deduced hypothesis that loudness is not totally determined by the sound pressure in the auditory canal. However, the regularities of the SLD effect are not yet exactly known.

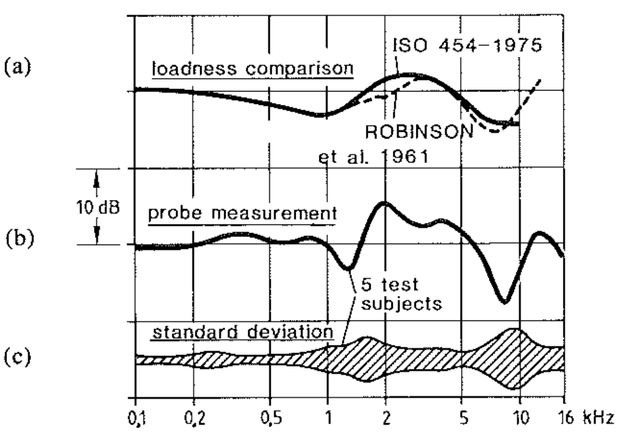

Fig. 6. (a) Acoustic relationship between sound pressure levels of narrow bands of noise in a diffuse field and in a frontally incident free field for equal loudness. (b) Difference of transfer functions of outer ear (free field minus diffuse field). Probe measurement. (c) Standard deviation of measurement (b).

2.6 Requirement of Physical Measurements

Considering the results of these experiments, one can already conclude that the loudness comparison method is unsuitable for determining the (physical) transfer function of headphones. Loudness is demonstrably a parameter of perception, which is particularly dependent on the parameters of spatial perception.

Headphones which are defined to have a totally flat frequency response using the loudness comparison method represent the loudness perceived either in the free field or in the diffuse field. Strictly speaking, they represent the loudness perceived in the reference sound field under defined listening conditions (Relevant parameters are, for example, sound pressure, test signal, hearing with one or two ears, head fixed or not fixed.) This type of headphone (it may be called loudness-calibrated headphone) is of basic interest in psychoacoustic research, because the calibration is correct for certain loudness-matching experiments.

Perhaps the most demanding application of calibrated headphones is in the measurement of hearing performance. However, it is not evident that loudness-calibrated headphones have the correct calibration for measurement of the hearing threshold. The loudness-calibrated headphone simulates the loudness perceived in the reference field. It does not reproduce the referring sound level in the auditory canal [10], [12] (SLD effect). Experiments have shown that the SLD effect cannot be observed at the hearing threshold. Consequently the sound level in the auditory canal cannot be correct when carrying out measurements of hearing threshold and using loudness-calibrated headphones. It is suggested that the sound level is too high, in particular at

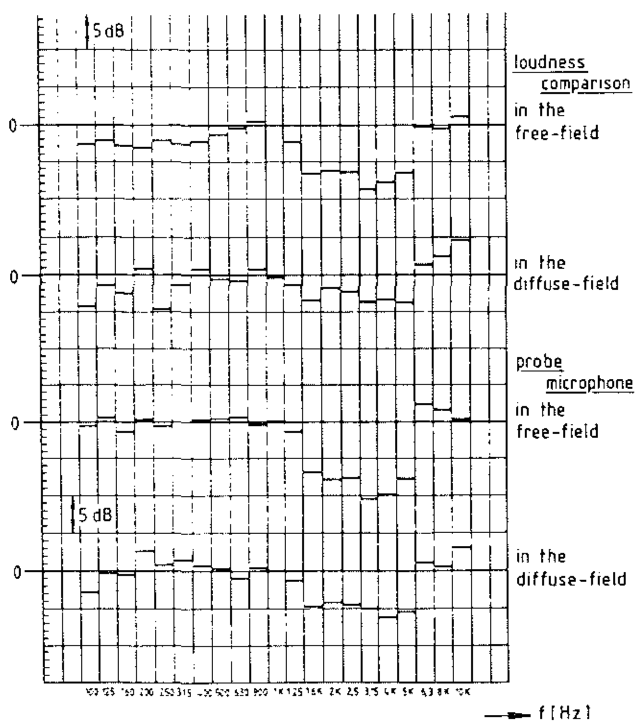

Fig. 7. Comparison of measurement methods. One-third octave band of pink noise. Measuring object—HD 430 (Sennheiser). (From [10].)

low frequencies. To clear up these questions, experiments should be carried out measuring the absolute threshold not only with loudness-calibrated headphones but also with threshold-calibrated headphones, and comparing the results.

Overall it may be concluded that the loudness comparison method is a suitable method for calibrating headphones used for loudness matching experiments, but it produces errors in determining the (physical) transfer function of headphones, which is required for high-quality headphone listening.

Several other subjective measuring methods have been compared at IRT in order to find the most adequate one. Particularly the works of Schröter [16], Schröter and Els [17], and Humes [18], dealing with measurements of hearing protectors, have been considered. Experiments at the IRT have been carried out, testing a "masked bone-conduction threshold" procedure, similar to the one Humes tested [18]. However, the general conclusion is that subjective measuring methods require complicated procedures and much time for getting objective data and for avoiding undesired psychoacoustic effects (such as the SLD effect). The requirements are not feasible for a headphone standard. Physical transfer functions should be measured directly by physical methods.

Recently Sahr [1] suggested that just these psychoacoustic effects, which experimenters had been trying to avoid, have to be included in the measurement. He considers in a hypothetical model the path of a sound signal which has to travel up to the final judgment in the human brain and concludes:

> One should assume that comparisons of loudness would be the most exact method of judging headphones. With this method, the sound of headphones is really judged as it is perceived by the test person. On the other hand, it might be noted that the measurements by probe microphone occur during the relatively early stages of the process.

However, this suggestion has not yet been examined. Some theoretical statements should be given here. Sahr suggests that the judgment "equal loudness at every third-octave interval" implies the judgment "equal timbre of broadband signal." This is questionable because loudness and timbre are different sensations [19], and this could only be examined in the reference sound field itself. According to the association model, this would signify that the adaptive process in the location-determining stage (represented by M^{-1}) is identical in experiment A (loudness comparison, narrow-band test signals) and in experiment B (timbre comparison, broadband program signals). However, current investigations [9], [12] show that the adaptation depends on the test situation (for example, the SLD effect depends on the bandwidth of the signal [11], [12]). Thus a test situation should be determined which ensures "equal loudness" in experiment A and "equal timbre" in experiment B.

What kind of reference sound field should be "correct" for obtaining the judgment "equal timbre"? The perception of timbre is not completely determined by the power spectrum of the sound field at the listening place. It is divergent in the nonreflection room, reverberation room, and listening room, and it depends on the kind of loudspeaker reproduction (mono, stereo, correlation of loudspeaker signals) [7], and so on. The processing in the brain is too complex, and a sound-neutral loudspeaker reproduction is not definable so far.

On the contrary, it has been shown that a sound-neutral headphone reproduction is definable. Subjective comparison judgments with loudspeaker reproduction are unnecessary. Only a "flat frequency response at the auditory canal entrance" has to be defined. The definition is derived by the integral over all free-field transfer functions of the outer ear, which can be measured in the diffuse field. The requirement "physical measuring in the diffuse field" is not derived from simulating the perceived timbre in the sound field, but from avoiding linear distortions when coupling the headphone to the auditory canal entrance. This is due to the psychoacoustical phenomenon that the localization process adapts to the loudspeakers, "whispering in the ears" [1].

3 PHYSICAL MEASUREMENTS

3.1 Probe Microphone Measurements

At the IRT the probe microphone technique has been developed further to a practicable and exact procedure, which is suitable for standardization [2], [20]. The probe is a miniature electret microphone (Knowles EA-1842), which has been provided with elastic braces to center it within the auditory canal (Figs. 8 and 9). The elasticity of these braces has been adjusted to ensure a firm fit as well as easy handling of the probe. When the probe is inserted, the microphone input is turned toward the eardrum (Fig. 9). This ensures that the measuring point is in the auditory canal and not in the area of the outer ear.

The microphone cable is made out of thin and very flexible wires. It is led out of the auditory canal by feeding a bow in the cable into the area of the concha and then fixing it underneath the pinna. This ensures that the position of the probe is well fixed during the measuring procedure.

The probe technique does not disturb sound propagation at the outer ear, and the natural acoustic coupling of the headphone is ensured.

The output voltage level of the microphone is measured (each one-third-octave band) when the test subject is sitting in the reverberation room and the loudspeaker is reproducing the test signals. Immediately after measuring the diffuse field, the test subject puts on the headphone carefully, and the output voltage level of the microphone is measured again during headphone reproduction. This measuring procedure is repeated twice.

In order to verify the fixed position of the probe in the auditory canal, the measuring results should be compared. The standard deviation of the values obtained with the three headphone measurements should be within ±2 dB, even at high frequencies. A variation greater than ±2 dB might be caused by an uncertain acoustic coupling of the headphone or by an intervening change in the position of the probe. An intervening change in the probe position can be excluded by checking the fit of the probe and repeating the measurement (maybe with another test subject). In the (rare) case of uncertain coupling of the headphone it would be useful to take more than three measurements for each test subject.

The measuring procedure should be carried out with a minimum of five test subjects. The individual headphone transfer responses have to be determined by computing the difference "output voltage level of the microphone (headphone sound) related to the input voltage level of the headphone" minus "output voltage level of the microphone (diffuse field sound) related to the sound pressure level of the diffuse field at the measuring point." The average values represent the diffuse-field response of the headphone to be calibrated.

Because the measurement is relative, the probe does not need to be equalized, and the geometrical dimensions, like the position of the probe, have practically no influence on the results. Errors in the measurements, which can conceivably occur due to the differences in the termination of the entrance to the auditory canal (either diffuse field or headphone is coupled to the auditory canal entrance), can be disregarded since the headphones of the usual design include a sufficiently large termination volume in comparison with that of the auditory canal [21]. More details are presented in [20]; the measuring technique is described in an IRT proposal [22].

In the last two years 20 headphones have been measured at IRT using this technique. This practical experience led to the proposal of specifications with regard to the reproducibility of the results [20]. In summary, depending on the reproducibility of the fit of the headphone, the maximum spread of the measured diffuse-field responses is in the range of ±1.5 to ±2.5 dB. A typical result is shown in Fig. 10. The diffuse-field response of the DT 880 (Beyer) has been measured on three groups of five test subjects each. The individual results (upper thin curves) and the average (upper fat curve) show that the spread of the measured headphone responses is less than ±2 dB at high frequencies. In the frequency range of 0.1–2.5 kHz it is less than ±1 dB.

It has been found that headphones of circumaural design (soft cushions do not press the pinna but the surrounding area) normally obtain a reproducibility of responses in the range of ±1.5 to ±2 dB. The best reproducibility (±1.5 dB) was found at the Stax SR Lambda (electrostatic type with circumaural design). It can be concluded that the accuracy of the probe measurement in the diffuse field is better than ±1.5 dB (five test subjects) in the frequency range of 0.1–12.5 kHz.

The individual diffuse-field responses of Stax SR Lambda are plotted in Fig. 11 (thin values). The fat plotted (averaged) curve is the diffuse-field response of this headphone. The deviations of the individual diffuse-field responses are significant in the frequency range of 1.6–16 kHz; they are mainly caused by in-

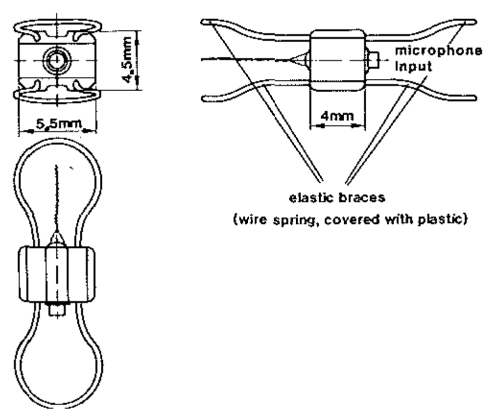

Fig. 8. Probe microphone using miniature microphone type Knowles EA-1842.

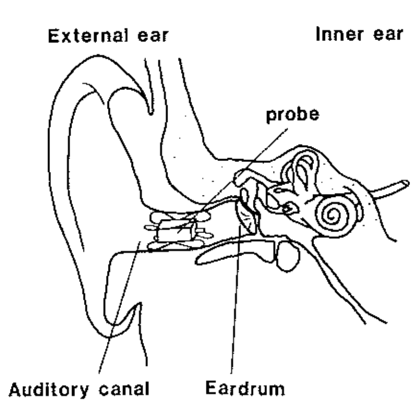

Fig. 9. Schematic cross section of human ear with inserted probe microphone.

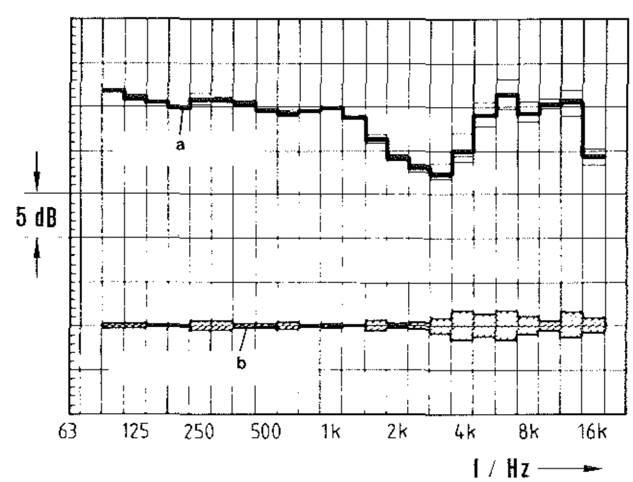

Fig. 10. Diffuse-field responses of DT 880 (Beyer). Three measurements of three groups of five subjects each: (a) Thin curve: three results of three measurements; thick curve: average result of three measurements. (b) Spread of the measured responses.

dividual differences of the outer ears. These data may be compared with those obtained with another headphone, for example, the Beyer DT 48 (Fig. 12). The deviations of these individual diffuse-field responses are particularly high. It can be concluded that 1) the SR Lambda is less dependent upon the physical individual properties of the human ear than the DT 48, and 2) the reproducibility of the fit of the SR Lambda is better than that of the DT 48.

Discussing the measuring technique, a general fact can be deduced from a comparison of the results in Figs. 11 and 12. The deviations of the individual headphone responses cannot be used as a criterion for judging the measuring method. The deviations are not caused by the measuring technique (provided there is no interfering change of the position of the probe in the auditory canal), but by the headphone design and the properties of the human ear. In order to achieve predictable performance with any headphone on a variety of individual ears, it is necessary to measure the deviations exactly. For instance, this is not possible when using the loudness comparison method, because both capsules of the headphone (left and right ears) are measured simultaneously. The practical advantages of the probe microphone measurement are as follows:

1) The test subject has nothing to do during the measurement. This makes it possible for untrained people to participate, and it also avoids errors caused by tiredness or lack of concentration. The result is independent of the performance of the test subject (objective measurement).

2) Consequently only five instead of eight test subjects are needed to get sufficient reproducibility.

3) The measuring procedure needs less time, particularly if an automatic fast Fourier transformer analyzing system is not used.

4) Only one capsule of the headphone (left or right) is measured. The measuring result is not the average of both capsules. Additional coupler measurements (according to IEC Publication 268 and DIN 45 619) are not necessary.

5) Very high frequencies can be used without problems.

Some measuring results are presented in Fig. 13. It should be mentioned that none of the headphones measured at IRT had a flat diffuse-field response.

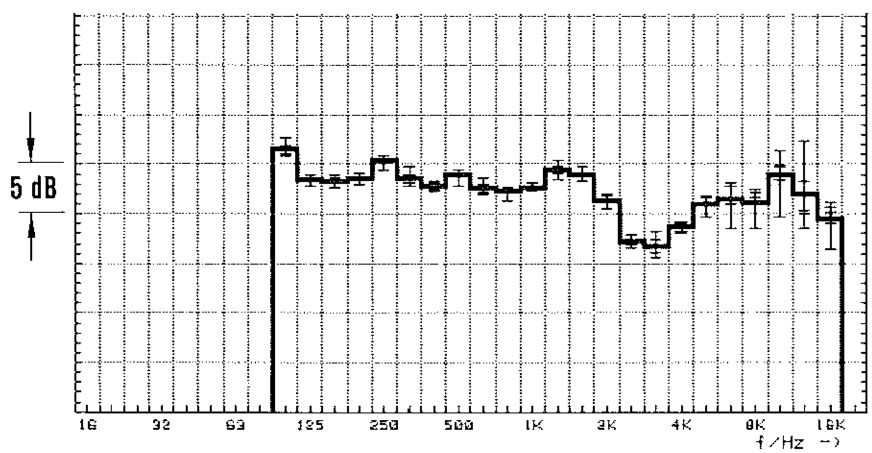

Fig. 11. Diffuse-field responses of Stax SR Lambda Prof. Individual and averaged values.

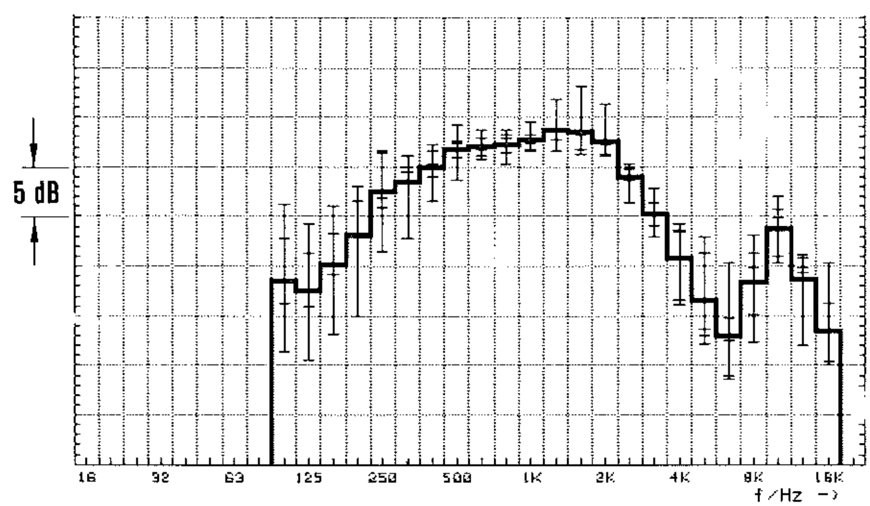

Fig. 12. Diffuse-field responses of DT 48 (Beyer). Individual and averaged values.

3.2 Dummy-Head Measurements

Another physical measurement method is the use of a dummy head instead of the human head. The dummy-head method seems to be advantageous in comparison with the probe technique in principle for the following practical reasons.

1) The dummy head can be standardized. Results of different laboratories should have maximum conformity.

2) The dummy head can be calibrated once so that a reference measurement in the reference sound field is not necessary.

3) The dummy head needs only a very small silent chamber. No measuring errors will occur by swallowing hiccups, sneezing, or coughing.

4) The dummy head does not require insertion of a probe; there are no problems with the danger of hurting the eardrum and with hygiene.

5) Dummy-head measurements can be carried out more quickly.

But previous experiments with this method have shown that the existing dummy heads do not replicate important acoustical and mechanical properties of the human head, which are essential when coupling a headphone to the auditory canal. Toole [1], Schröter [16], and Schröter and Els [17] give surveys of these problems.

Schröter and Els have developed a special dummy head suitable for the measurement of earmuffs as well as earplugs [17]. This measuring head replicates the mechanical characteristics of the human head at the area of contact between the protector (or headphone) and the head. The mechanical impedances of 100 subjects at four points around the pinna and the shear impedances of the auditory canal walls were measured. Layers of polyurethane rubber are used to set the average of the impedances. Further, the measuring head has an "ear simulator" (realization of the acoustical eardrum impedance).

Recently Schröter, Spikofski, and Theile [21] have carried out investigations on headphone measurements using this dummy head. Comparing the results of these measurements (headphones of different designs were used) with the results achieved with the probe microphone technique (Sec. 3.1), the following can be concluded.

The diffuse-field responses of headphones, measured at the dummy head, represent the individual diffuse-field responses measured with any test subject. In some cases leakage problems occurred, because the replication of the elasticity of the human pinna is not yet sufficiently exact. This problem should be solved soon. As an example, in Fig. 14 the individual diffuse-field response of the headphone DT 880 is plotted, measured at the dummy head (fat curve). Comparing this result with the results achieved with five subjects (thin values), one can see that the curve achieved with the dummy head corresponds to the curve achieved with the subjects, but it does not represent the averaged curve (see Fig. 10).

Similar results had been obtained when measuring other headphones. In comparison with the referring average values, no systematic difference was found. This means that the acoustical coupling headphone–dummy head is incorrect. This dummy head provides typical outer ear transfer functions [17], but the acoustical and mechanical properties do not allow achieving average diffuse-field and free-field responses.

It is suggested that it will not be possible to construct

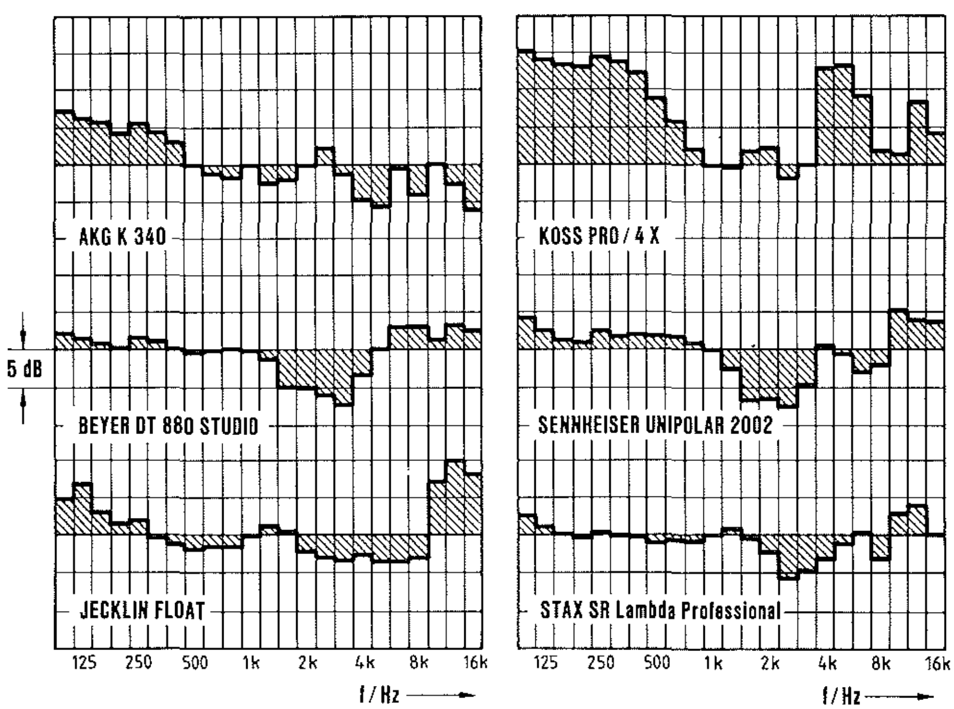

Fig. 13. Diffuse-field responses of six headphones.

an "average outer ear," which can be used as coupler, independent of the design of the headphones. But it seems possible to get relevant results using a number of different dummy heads, which represent individual human heads [21]. Further it has been proposed in [21] to use interchangeable pinna replicas on dummy heads to simulate different heads. This method avoids the problems caused by couplers, replica ears, and dummy heads [1], but it conserves all of the advantages of the dummy-head measuring methods mentioned.

4 SUBJECTIVE ASSESSMENT

4.1 Listening Tests

Two tests on the subjective assessment of headphone quality have been carried out in order to determine the preferred diffuse-field responses of headphones [2], [23]. The test material was carefully selected during preliminary tests. Recording engineers were asked to determine relevant material. It consisted of classical music, jazz, "pop" music, and speech. For the classical sequence the same extract was taken from five different recordings of a classical piece. The recordings were made by different recording engineers over the last 20 years, thereby ensuring that the test results would not be influenced by a tonal reproduction peculiar to any recording engineer.

4.1.1 Listening Test 1

Seven headphones were used. Their diffuse-field responses were measured (probe measurements, see Sec. 3.1, diffuse or free field as reference). During the listening test the subject could choose among three equalization characteristics: flat diffuse-field response, flat free-field response, and without equalization. The first two were produced by individually adjusted electrical equalization, as required. Only one headphone was used during a single session.

Twenty-four subjects participated in the listening tests. The majority of the persons were employed in broadcasting (including four recording engineers) and experienced in assessing sound quality. For each headphone and each test item a preference had to be stated for one out of the three sound reproductions, first using the assessment category "naturalness" and then that of "pleasantness." The results are summarized in the following. (Details are given in [2].)

1) With all the headphones there was a preference for diffuse-field equalization due to the assessments "more natural" and "more pleasant." The free-field equalization was rejected.

2) The preference for the diffuse-field equalization over that of unequalized response was less significant in the case of two headphones (Stax SR Lambda Professional and Beyer DT 880). This was in accordance with the measured results for those headphones having the best (that is, the most flat) diffuse-field response compared with the unequalized response of the other headphones (Fig. 13).

3) The degree of preference for the diffuse-field equalization was dependent upon the test material.

Overall, a general superiority of the diffuse-field equalization was found, independent of the headphone design, the test material, and the assessment category.

Furthermore, when comparing the tone colors produced by the various headphones with diffuse-field equalization, only a small range of variations was found. The tone colors produced by headphones of quite different designs were surprisingly similar when electrical equalization was added.

4.1.2 Listening Test 2

The procedure and group of subjects were similar to those for listening test 1. Only one headphone was used (Stax SR Lambda Professional) and only the assessment category "more natural." New test material was selected with regard to various microphone techniques and types of music. (More details are given in [23].)

The results correspond well to those of listening test 1. With each test item the diffuse-field equalization was preferred. The performance of this high-quality type of headphone can be enhanced by equalizing the original diffuse-field response to be flat.

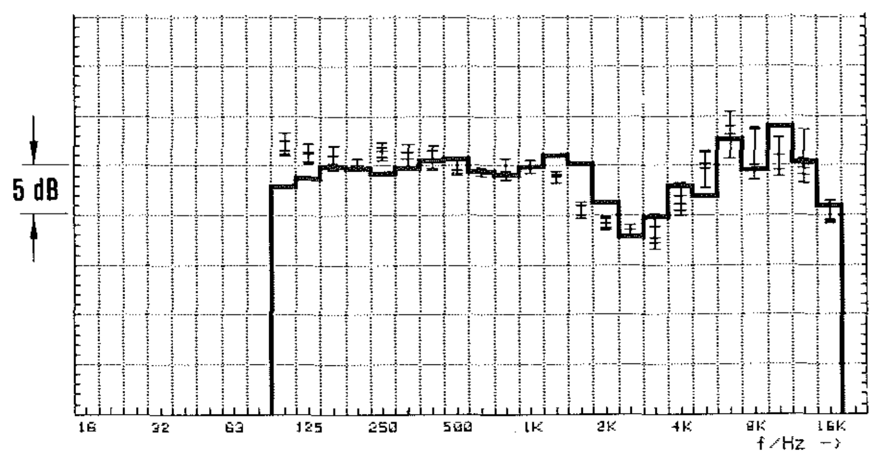

Fig. 14. Diffuse-field responses of DT 880 (Beyer). Fat curve—dummy-head measurement; thin values—probe measurement, one subject.

The result is important because it is achieved with a high-quality electroacoustic headphone which might be considered to have an exceptionally good phase and impulse response. These quality parameters should not influence the assessment of tone color. This is a prerequisite for determining the "correct" equalization by subjective assessments.

The results were achieved with a wide range of different pieces of music. Most of the test subjects were not irritated by assessing the reproduction of "pop music" with the category "naturalness." The results relevant for "pop music" did not differ from the others.

4.2 Other Subjective Assessments

The properties of the diffuse-field equalization have been discussed with many audio specialists, recording engineers, headphone manufacturers, audio laboratory engineers, and so on. In addition, audio conventions and certain workshops, discussing production and reproduction problems, were used to demonstrate the performance of the equalization with different headphone design. Analyzing these discussions, almost complete consensus was found among recording engineers and audio laboratory engineers. Using various music recordings of the recording engineers and test material from other laboratories, it was found that the judgment depends only slightly on the piece of classical music. For most of the pieces the predominant judgment was "correct," "neutral," or "natural."

However, it could be observed that in the case of certain productions the tone color seems not to be optimal, being described perhaps as "too much presence" or "slightly too sharp." This effect has been observed carefully. It became clear that the effect must be explained with shortcomings of the recording technique: the distances of the microphones to the musicians were chosen as too short. The resulting characteristic of the tone color can be heard even by means of loudspeaker reproduction, but less clearly. Using diffuse-field equalization headphones, the nearness of the microphones is identified as "unnatural."

A high-quality headphone used in studios for judging sound quality, in particular for judging tone color, should not "beautify" any shortcoming of the recording technique. There is a serious interest in the studios in obtaining an absolutely correct reproduction of t[illegible] crophone signal, and this applies also when mon[illegible] with headphones. A diffuse-field equalized head[illegible] could satisfy this demand. This is an important [illegible] of all the discussions and experiments carried [illegible] cooperation with many experts. In addition, reco[illegible] with unnatural presence and an unsatisfying rep[illegible] tion of distances, caused by the nearness of [illegible] phones, have been considered unsuitable for judging headphones (as well as loudspeakers) in the majority of cases. One can recognize the tendency in the recording technique of placing the microphones at a "more natural" distance. Nevertheless, the problem of selecting test material is evident. Relevant test material has not yet been defined.

Different recording techniques influence the assessments of the sound quality. It is incorrect to imply that the recording technique "has an influence on the quality of the headphones" [10]. For example, the extreme nearness of the microphones leads to a characteristic tone color, which should be reproduced with high-quality headphones. Thus the quality of this *production* is not the best, and it might be improved by equalizing the signal at the amplifier, but not by changing the headphones.

However, in general headphone manufacturers agree to the proposed definition of headphone equalization. In cooperation with the IRT, some manufacturers have developed high-quality studio headphones. In Fig. 15 the diffuse-field responses are plotted for three studio headphones which are available now.

5 CONCLUSION

It may be summarized that the physically defined diffuse-field response of a headphone is the relevant quality parameter as regards the frequency response. A flat diffuse-field response, measured with a probe microphone in the auditory canal of real ears, defines "the optimum 'correct' performance" [1].

The result has been deduced from the association model with regard to spatial hearing. It can be considered the particular result of an investigation concerning the general problem of the compatibility of production and reproduction [6].

The problem of compatibility is illustrated in Fig. 16. Both for production and for reproduction there is one system relating to space and one relating to the head. (These terms are defined in [6].) Transmissions along the diagonal paths, that is, stereo production/loudspeaker reproduction (space-related process) on the one hand and dummy-head stereo production/headphone reproduction (head-related process) on the other, are by definition compatible. In principle, any value of signal equalization may be applied between production and reproduction. However, conventional stereo

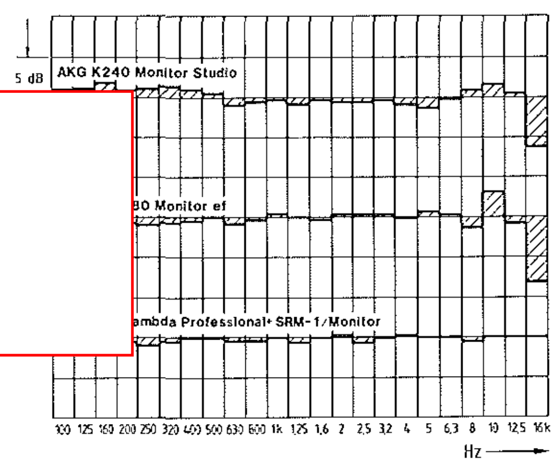

Fig. 15. Diffuse-field response of three high-quality studio headphones (according to proposed standard DIN 45 619, part 3).

is basically incompatible with headphone reproduction, and dummy-head stereo is basically incompatible with loudspeaker reproduction. In both cases the system consists of a space-related process and a head-related one. The incompatibility arises from the processing of the auditory location-determining stage of the auditory system (see Sec. 2.1 and 2.2).

It has been shown [6], [24], [25] in both instances that equalization of the connection between the sound production equipment and the reproduction equipment must not be based on a single reference direction, but that all transfer functions of the outer ear must be replaced by a corresponding average transfer function in order to ensure that tone color defects are kept to a minimum. This is achieved by taking as the reference the diffuse sound field.

The general solution of the problem of compatibility has been subjectively assessed referring to the equalization of the dummy head (KU 81, Neumann) [25], [26] as well as referring to the equalization of headphones [2], [23], [27].

In addition, in the case of dummy-head stereo and headphone reproduction, a headphone with a flat diffuse-field response is naturally the correct headphone for reproducing KU 81 recordings. Further, headphones which are now available on the market delivering a satisfying tone color neutrality already have nearly a flat diffuse-field response. They already correspond to the submitted standard DIN 45 619, part 3, much better than to the present standard DIN 45 619, part 1, or IEC Publication 268-7 (1981). Furthermore, headphones with an exactly flat diffuse-field response, corresponding to the submitted standard DIN 45 619, part 3, are now available.

Headphone manufacturers are aware of the tone color defects of headphones with exact equalization according to the present standard. Attempts are still being made to achieve improved total reproduction by extending the range of tolerance laid down in DIN 45 500, part 10, and IEC Publication 581-10. However, increased tolerances are in fact the wrong course. On the contrary, the tolerance range for the prescribed equalization should ultimately be reduced.

As a result of this investigation it has been proposed

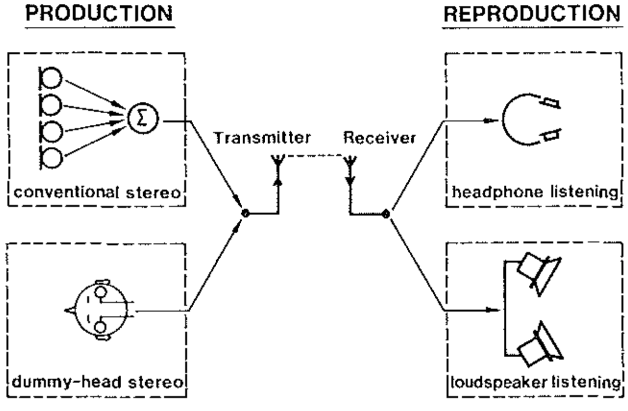

Fig. 16. Defining the compatibility of a certain sound production and reproduction process.

to work out new national and international standardization for high-quality headphones. Contrary to the present standards, which require free-field response and loudness comparison measurements, the new standard for high-quality headphones should set out a flat diffuse-field transfer function and probe measurements with test subjects. In the future measurements might be carried out with a set of dummy heads.

Practical experience has shown that the diffuse-field equalization according to proposed standard DIN 45 619, part 3, permits defining tolerances with narrow limits.

Such a provision could then be used to set minimum requirements for high-quality studio headphones, as in the case of microphones, loudspeakers, and other studio equipment. In order to ensure a sufficiently uniform sound reproduction, the proposed standard would be useful in the case of subjective judgment of program material, referring to the international program exchange as well as to the assessment of sound quality (CCIR Recommendation 562-1).

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THE AUTHOR

Günther Theile was born in Rotenburg, West Germany, in 1943. He studied electronics at Bremen Technical College and worked with the Philips Company in Bremen in the field of digital electronics. In 1970 he studied psychoacoustics/communications theory at the Technical University of Berlin. He received his Ph.D. from the Technical University of Berlin in 1980 with a thesis on "Localization in a Superimposed Sound Field."

After two years with the Heinrich-Hertz-Institut in Berlin he moved to Munich's Institut für Rundfunktechnik (IRT) in 1977 where, since 1980, he has led the group dealing with audio production and reproduction systems, psychoacoustic research and assessment of sound quality.

Dr. Theile is the author of about 30 papers and holds 10 patents in the fields of psychoacoustics (spatial hearing, stereophony), microphone technique, headphone reproduction and audio signal processing (variable dynamic range, low-bit-rate-coding). He is a member of Verband Deutscher Tonmeister and currently engaged in the work of CCIR, Study Group 10 C.