Study on the standardisation of studio headphones*

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Current IEC and CCIR texts make no mention of headphones, although their use is appropriate in certains instances. A study of recent work on the properties of spatial hearing shows that the free-field equalisation applied to headphones cannot give good results. The equalisation is more satisfactory if reference is made to the diffuse field defined on the basis of average value of the transfer functions of the outer ear in different directions.

The article shows that methods based on the measurements of loudness produce wrong results and it also reports on subjective experimets carried out using commercially available headphones. Finally, it proposes an action programme aimed at drawing up an international standard, applicable to headphones.

Study on the standardisation of studio headphones*

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1. Introduction

Headphones are relatively rarely used in studios although they are not inferior to large commercially available loudspeakers as regards transmission bandwidths, non-linear distortions, maximum acoustic pressure etc. There are a variety of reasons for this. The main one is the phenomenon of " localisation in the head ", which means that in the case of intensive stereophonic signals such sound events appear to occur either within the head or in its neighbourhood. This incorrect assessment of distances corresponds to a considerable loss in spatial reproduction, so that stereo productions may be evaluated more comprehensively using loudspeakers rather than using headphones.

Nevertheless, if these drawbacks are disregarded, headphone reproduction has advantages which 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 neighbourhood. In addition, headphones can considerably attenuate the ambient noise in the reproduction area so that the dynamic range of the programme signal can in fact be achieved without any additional constraint. As a result, in many cases headphone reproduction makes possible more concentrated listening ; it is less likely to cause disturbance and it is therefore frequently preferred to loudspeaker reproduction by listeners.

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

As a result, for radio purposes headphones should be considered to be as important as loudspeakers. The use of headphones is indispensable for listening to Kunstkopf productions, but it is also necessary for listening to productions of other types in poor conditions; it is also a necessary complement to loudspeaker reproduction in the case of all normal productions inasmuch as many listeners like using headphones.

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 by as much as 10 dB the figure obtained using loudspeakers at the same sound intensity. Similar differences occur in the case of the quality losses caused by clicks (caused by bit-errors in digital transmission), by quantification errors, non-linear distortions, etc.

As regards subjective assessment of the quality of sound transmission, CCIR Recommendation 562-1 gives important indications as to the grading of quality, choice of test programme material, test persons and test procedures. It also contains recommendations as to listening conditions, but these apply to loudspeaker reproduction only. There is nothing to indicate that any assessment of quality when headphones are used is envisaged.

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This is a significant omission, not only for the reasons set out above, but also because headphone listening conditions can in principle be defined with great accuracy and can easily be reproduced without any systematic error. The same does not apply to listening to loudspeakers. International efforts at harmonising the acoustic and geometric characteristics of sound control rooms and listening rooms have not, for understandable reasons, so far produced an adequate level of harmonisation. Neither EBU Recommendation R22-1980 nor the proposals contained in CCIR Report 797-1 provide guaranties of sufficiently harmonised listening conditions. There can be no expectation in the future of major progress in the standardisation of loudspeaker reproduction, at least at the international level.

Conversely, headphone reproduction offers optimum preconditions for practicable international harmonisation of listening conditions. Because it is independent of the geometric and acoustic properties of the listening area, standardisation can be achieved with very little effort and can be accurately maintained without difficulty. In addition, assessment tests can be carried out using a great number of test persons at the same time. Tolerances for many quality defects are even lower than in the case of corresponding loudspeaker reproduction. Only those influences which affect the characteristics of the stereophonic sound-image between the loudspeakers should be assessed by means of reproduction through loudspeakers.

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

Recently, in connection with the further development of Kunstkopf stereophony, a general solution to the problem of compatibility between various processes of sound signal production and reproduction has been found [1]. In close relation to this process, theoretical conceptions as to the function of our hearing in spatial listening are expanded and described using a localisation model known as the association model [2]. This provides a unified explanation of all major phenomena of spatial listening and this will be used to define appropriate studio headphones.

2. Consequences of the association model

2.1 Operation of the model

The 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 of these two processes occurs by means of an associatively guided pattern selection : a momentary stimulus, derived from a sound source, initially

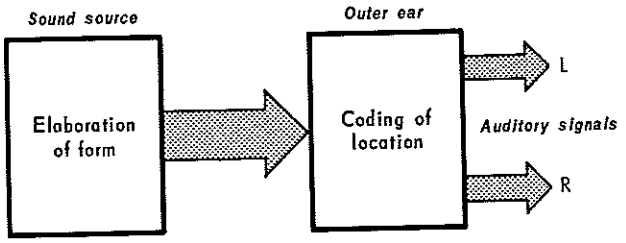

Fig. 1. — Origin of the two fundamental characteristics of a sound event.

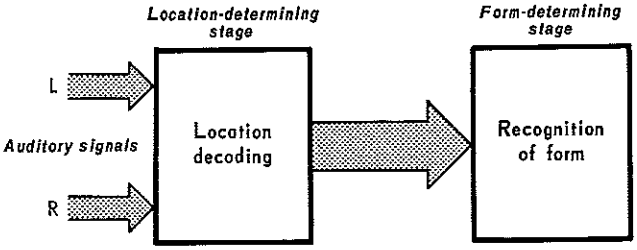

Fig. 2. — Origin of the two fundamental characteristics of hearing.

induces a local association and secondly, a form* association. The characteristic feature of the localisation model resides in the two-dimensional processing of the stimulus. It contains not only the stage of processing that determines the localisation, but also the stage that determines the form. Both stages must be gone through for the stimulus to achieve a form of perception *(Fig. 2)*. Accordingly, both processes jointly determine in every instance the properties of the sound event. This is fully in accordance with both elementary points of sound perception : received audio signals must be referred back to the properties of sound sources that always occur together, but are independent of each other; that is, location and form *(Fig. 1)*.

Fig. 3 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 localising stage, represented by the transmission function M^{-1}, inverse to 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 transmission function M^{-1} which, as a result of the associative recognition of the model, is in inverse relation to M, the transmission function of the external ear, which depends on the location.

The adaptive operation of the localisation stage gives rise to two consequences with regard to the definition of optimum headphones. These are examined briefly below.

2.2 Objections to "free-field" equalisation

The inverse filtering M^{-1} frees ear-signals from any influence by the outer ear before the source signal reaches the form-determining stage. This means that in natural hearing, spectral features caused by the

* The word "form" is used here in its *Gestalt* meaning : i.e. a pre-existing structure in the brain, to which the perceived structure is directly comparable (Ed.).

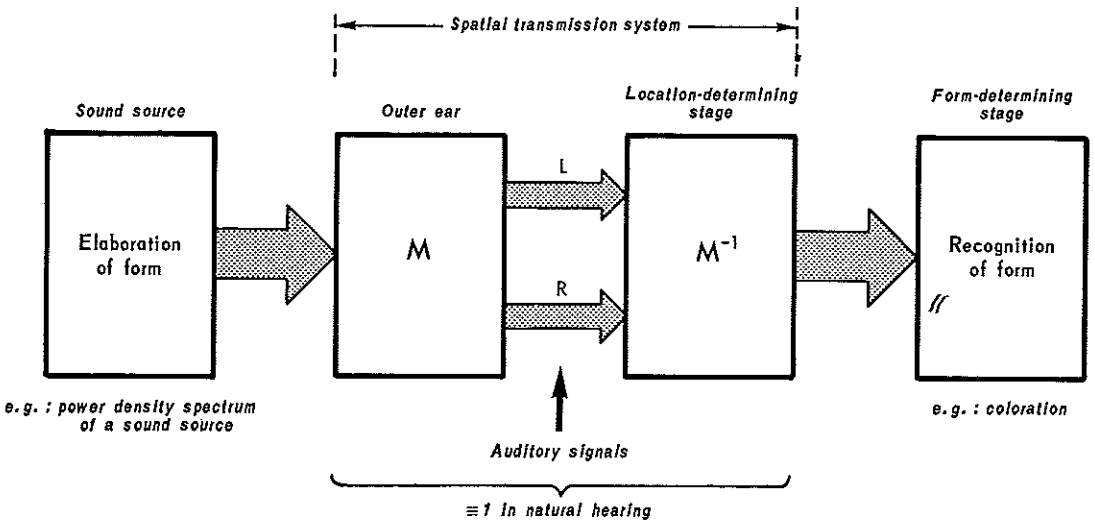

Fig. 3. — Operation of the system of spatial transmission of hearing.

directivity of the outer ear are apprehended in such a way that they do not occur as coloration *(Fig. 3)*. The association model indicates that perception of coloration is independent of the source location. This coloration phenomenon can be verified readily but has been described in publications only very recently [3].

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

On the other hand, in headphone reproduction the effect of the outer ear is simulated by the standardised free-field equalisation of the headphones. If this simulation were sufficiently precise, the localisation process would occur for a monophonic signal and the sound event would arise in the median plane outside the head (more precisely at the reference point for the headphone equalisation) [4, 5]. However, the headphone transfer function can practically never achieve adequate simulation in reproduction of intensity stereo signals [6]. In that case, the localisation process adapts to the headphones [1], manifesting itself as localisation in the head (" phantom source in the head " [2]). However, that means that the spectral characteristics of the ear-signals caused by the headphones equalised for the free-field condition intervene at the " form " stage and not at the localisation stage : the M^{-1} inverse filtering does not occur and coloration errors result *(Fig. 3)*. Uniform free-field transfer function by headphones therefore in principle gives rise to coloration defects.

2.3 Objections to loudness measurement

The second consequence does not affect the definition of the headphone transfer function but its measurement using the loudness comparison method.

According to the association model, the effect of the outer ear on the ear-signal is compensated in the localisation process. The linear distortions caused by the directive filter constituted by the outer ear do not in principle affect coloration. In other words, our hearing cannot be conceived as a microphone with a fixed weighting filter; the perceptions of loudness and coloration 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 localisation process, which is related to the formation of the event perceived.

It follows that loudness comparison and measurements made using a probe must inevitably produce different results if sound events with differing locations are being compared. The loudness comparison method can only be used in determining the transfer function of the external ear and those of headphones if either the location of the sound sources being compared is totally eliminated or if both sound events are heard at identical points. These two conditions are not met by measurements made in compliance with IEC Publication 268-7 or DIN 45 619.

3. Definition of a studio headphone

It has just been theoretically deduced from the association model that a uniform transfer function in free-field equalisation causes coloration distortion and that the method of loudness comparison produces errors in determining the headphone transfer function. More suitable criteria must now be given for the definition of high-quality headphones.

3.1 Uniform transfer function in diffuse field

The question of the optimum reference for headphone equalisation is dealt with generally in [1]. It can be regarded as a particular aspect of the general problem of the compatibility of production and reproduction.

The problem of compatibility is illustrated in *Fig 4*. Both for production and for reproduction, there is one system relating to space and one relating to the head

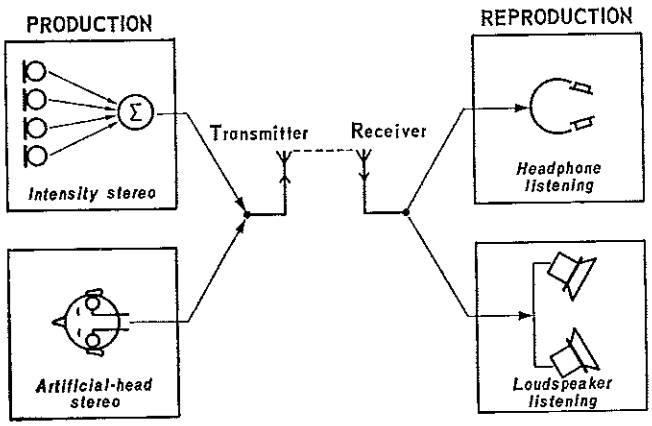

Fig. 4. — Compatibility of certain sound production and reproduction processes.

(these terms are determined in [1]). Transmission along the diagonal paths, that is intensity-stereo loudspeaker reproduction (space-related process) on the one hand, and Kunstkopf stereo - headphone reproduction (head-related process) on the other, are by definition *compatible*. In principle, any value of signal equalisation may be applied between production and reproduction.

However, intensity stereo is basically incompatible with headphone reproduction and Kunstkopf 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 ear-signals in the localisation stage of listening (see Section 2). Reproduction free of sound distortion is possible only if :

a) in loudspeaker reproduction of Kunstkopf signals, the source location of the artificial head corresponds to the reference direction of its correction ;
b) in headphone reproduction of intensity stereo signals, the listening location corresponds to the reference direction of the headphone equalisation.

It follows that :

a) the free-field adaptation of Kunstkopf signals is in principle the wrong equalisation for loudspeaker reproduction ;
b) standardised free-field adaptation of headphones is in principle the wrong equalisation for the reproduction of intensity-stereo sound.

It has been shown [1, 7] in both instances that equalisation 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 the coloration is kept to a minimum.

It has already been shown in practice that diffuse-field adaptation of an artificial head constitutes the optimum equalisation for loudspeaker reproduction [7].

On the other hand, diffuse-field adaptation of headphones with intensity-stereo signals has not so far been attempted. This project is for the moment based on purely theoretical considerations, but there are a number of practical indications that the term " free field " in DIN standard 45 619 and IEC Publication 268-7 can be replaced by the term " diffuse field ".

If headphones were actually to simulate the loudspeaker-auditory canal transfer function, the sound impression would be as poor as that of the loudspeaker in a non-reflecting area. This also applies to the use of " loudspeakers arranged for stereo operation " (LSE process [8]). The condition " loudspeakers in a living area " would be clearly better for determining the transfer function. Admittedly it involves a great number of parameters which are not easily definable, but the aim of providing a " sound picture simulating loudspeakers " would be achieved in greatly improved form. Under these conditions, it is understandable that neither the numerous measurements made using a probe on headphones (in free-field conditions) nor the precise simulations of specific transfer functions have been adopted by headphone manufacturers in an attempt to improve their product.

Headphone manufacturers are aware of the coloration defects of headphones with exact equalisation for the free-field conditions. Attempts are still being made to achieve improved tonal reproduction (see for example [9]) by extending the range of tolerance laid down in DIN standard 45 500. However, increased tolerances are in fact the wrong course. On the contrary, the tolerance range for the prescribed equalisation should ultimately be reduced.

Measurements on headphones show that the tolerances for standardised free-field adaptation are readily usable for diffuse-field adaptation (see Section 4.1.).

3.2 Measurements made using probes

IEC Publication 268-7 and DIN standard 45 619, stipulate that the free-field transfer functions of headphones are to be determined by " comparison of sound intensity with a progressive sound wave ". This procedure was introduced on the assumption that - irrespective of the headphone design - the same acoustic impression [10] is achieved as with loudspeaker reproduction if the headphones produce the same loudness for each one-third octave. This assumption seems evident.

Nevertheless, it has already been theoretically deduced that differing results for loudness comparison and measurements made using probes are to be expected if the loudness of auditory events with different locations are being compared (source location effect [11]). The source location effect occurs particularly in standardised headphone measurements. *Fig. 5* shows a number of differences in the free-field transfer functions of various headphones (loudness measurements minus those made using probes, from publications, and own work), including the average difference. It is clear that the figures given by loudness measurement are higher, particularly in the case of medium frequencies.

The divergencies 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 test subject who is unaware of the source location, and finally, the prevention of sound leakage.

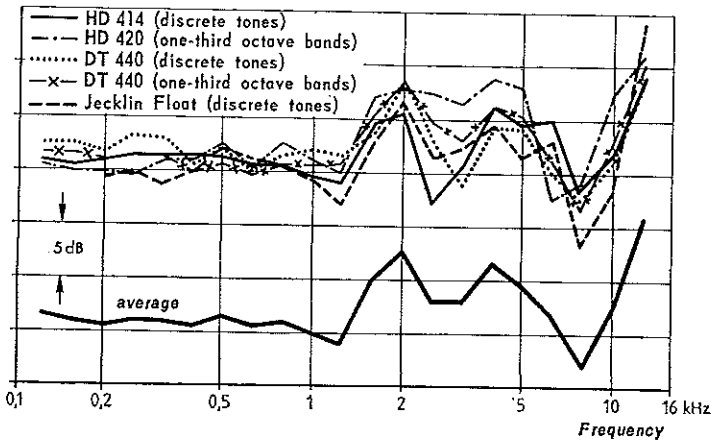

Fig. 5. — Free-field transfer functions for various headphones (variations between loudness measurements and measurements made using a probe).

However, such requirements are not feasible for a headphone standard. So far it has only been proved for low frequencies that under these conditions loudness comparison measurements produce the same results as measurements made using probes [11].

Measurements have further shown that even in a diffuse field the source location effect cannot be adequately suppressed, not even when comparing loudness with one ear. The perception of distance is different in the case of listening with headphones and listening in a reverberatory chamber. As a result, differences between the transfer functions for loudness comparison and those for measurements made with probes occur like those in comparison with free-field conditions.

The difference between the results for loudness comparison and those for measurements made with probes is smaller if the perceptions of distance accord better. For example, if loudness in free-field conditions is compared with that in diffuse-field conditions, it is easy to conclude with Robinson, Whittle and Bowsher [12] that loudness is determined solely by sound pressure at the ears. This conclusion is incorrect. Our own experiments and similar work carried out by Mathers and Landsdowne [13] show, for example, that differences in the range 7.5 to 14 dB between the sound pressure levels measured in the auditory canal with loudspeaker reproduction and those with headphone reproduction are found if the test subject considers both to have equal loudness. This effect depends on distance and the signal; headphone reproduction giving subjectively equal loudness produces a greater sound pressure level in the ear. Similar effects are observable in headphone reproduction when switching from Kunstkopf signals to intensity stereo.

Overall, it may be concluded that the loudness comparison method is unsuitable for determining transfer functions of the outer ear and of headphones. Loudness is demonstrably a parameter of perception which is particularly dependent on the parameters of spatial perception. Loudness is not totally determined by sound pressure in the auditory canal. Measurement by means of probes is therefore required, and this can be carried out very simply with a miniaturised electret microphone. It is sufficient to ensure that :

- the measurement point must be situated at least 4 mm behind the entrance to the auditory canal ;
- the measurement probe must not disturb sound propagation at the outer ear (up to 4 mm inwards from the plane of the auditory canal) ;
- the transfer function of the outer ear in the reference sound field and that of the headphones must be measured directly one after another on each test subject, without any intervening change, however slight, in the position of the probe.

The probe does not need to be equalised, as the outer ear and headphone transfer functions are expressed as a quotient (relative measurement). Because the measurement is relative, the position of the probe has practically no influence on the results. Errors in the measurements, which can conceivably occur due to differences in the termination of the entrance to the auditory canal, can be disregarded, as headphones of the usual design include a sufficiently large termination volume in comparison with that of the auditory canal. The time and apparatus required for making measurements with a probe is less than that needed for loudness measurements. Depending on the circumstances, measurement using a probe can be carried out nearly as easily as matching measurement : the task of obtaining the average of several test subjects can be dispensed with once a typical test subject has been found. A test subject can be regarded as typical if his " focussing factor " approximates to the figures given in *Fig. 6* (for measurement made using a probe) (see Section 3.3.). The typical test subject can in practice function as an optimum matcher in all measurements. In the future, the typical human outer ear may conceivably be replaced by a replica (artificial head).

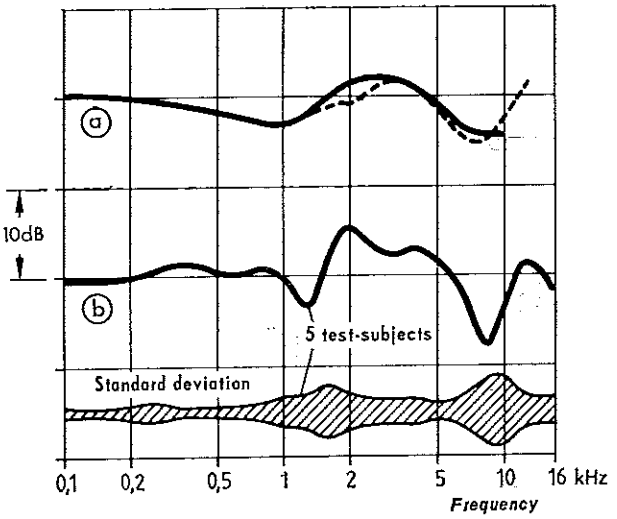

Fig. 6. — Focussing factor of the outer ear :
(a) loudness measurement in accordance with ISO Standard 454 (the average according to Robinson et al. is shown by a broken line),
(b) sound measurement.

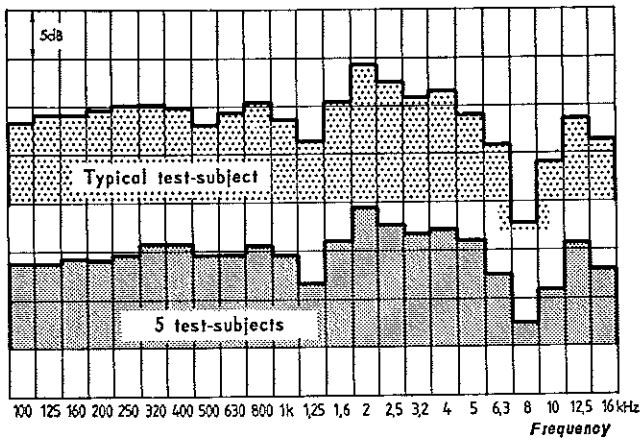

Fig. 7. — Focussing factor of the outer ear: measurements made using a probe.

3.3 Transposition of results

If the diffuse field is taken as the reference instead of the free field (frontal sound incidence), a specific difference in transfer functions results. *Fig. 6* shows the focussing factor of the outer ear; that is, the difference between the free-field transfer function for 0° and the diffuse-field transfer function. This quantity was measured by means of a probe on five test subjects. The average curve of loudness measurements [12] and the indication in ISO Standard 454 are given for purposes of comparison. The focussing factor is basically suitable for converting between headphone free-field adaptation and diffuse-field adaptation, and vice versa. *Fig. 7* shows that the focussing factor of a typical test subject is very close to the average.

It is therefore not necessary to measure the diffuse-field transfer function of headphones in a reverberatory chamber; the free-field transfer function can continue to be determined, albeit by means of measurements made using a probe. This can then be easily transposed into the diffuse-field transfer function using the focussing factor described above. If the reference selected is free-field conditions, measurements made using probes *(Fig. 7)* will result in headphones which suffer from linear distortions corresponding to the focussing factor curve (see Section 2.2.).

Furthermore, it is clear from the two curves in *Fig. 6* that loudness comparison measurements diverge from measurements made using probes, particularly at medium frequencies. These deviations are clearly less important in determining the focussing factor than in the case of headphone measurements, as there are fewer differences between the spatial characteristics of the sound events being compared (see Section 2.3.).

On the same basis as the curve in *Fig. 5* and the focussing factor (measurement using a probe) in *Fig. 6*, it is possible to produce a correction curve representing the difference between the free-field transfer function (loudness measurement according to standard) and the diffuse-field transfer function (measurement made using a probe) of headphones. In this way it might be possible to achieve an alternative application of loudness measurement, although this would require additional standardisation of diffuse-field adaptation and measurement made using a probe. However, in that case the extent of the differences between standard loudness comparison and standard measurement made with a probe would have to be clarified. The curve given in *Fig. 5* is merely indicative; it would have to be measured carefully in order to enable an accurately quantified transposition to be performed.

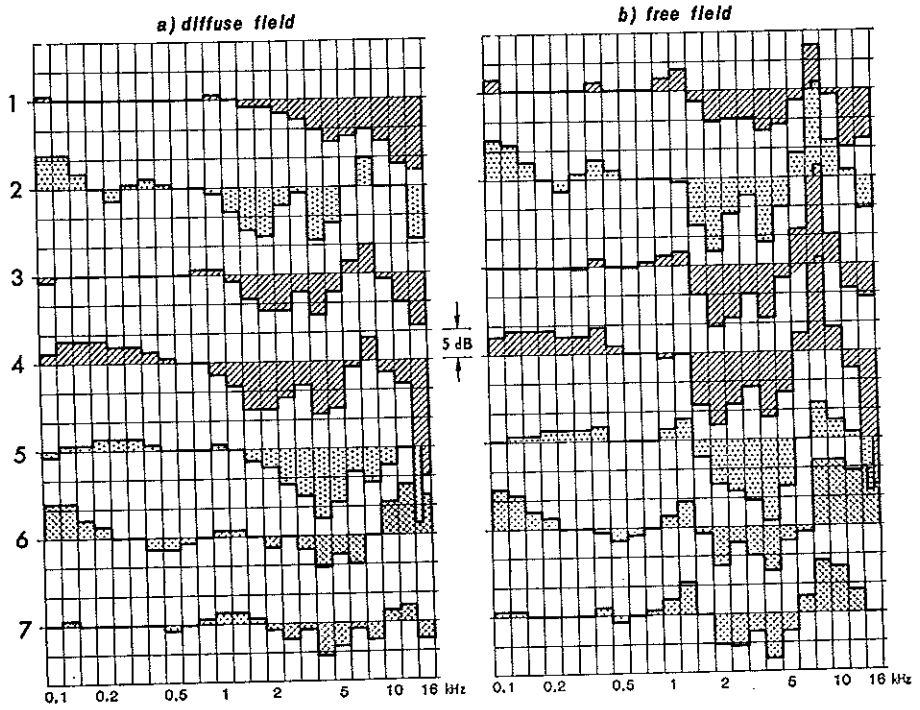

Fig. 8. — Transfer functions of several headphones.

The headphones are indicated by numbers which correspond to the following sets:

1 : DT 440
2 : DT 660
3 : DT 880
4 : HD 430
5 : HD 230
6 : Jecklin Float
7 : STAX-SR-Lambda

This numbering system is employed in all subsequent figures.

4. Quality assessment of headphones

4.1 Measurement on headphones

During a series of tests, free-field and diffuse-field transfer functions were measured on seven headphones of differing design. Measurements were carried out using a probe on a typical test subject. As in the case of Kunstkopf correction, test signals occupying one-third of an octave were used, as narrower-band measurement has drawbacks [7], whereas " third octave " frequency responses are adequate for assessing linear distortions.

A summary of the results is shown in *Fig. 8*. The first conclusion - as would be expected - is that all headphones are better adapted to diffuse-field reproduction than to free-field reproduction. It can also be seen that the headphones require quite a wide range of equalisation. Finally, it is evident that one good-quality type of headphone, the STAX-SR-Lambda, is particularly well-adapted to diffuse-field conditions.

4.2 Listening tests

Tests were carried out to examine whether diffuse-field adjustment produces optimum tonal neutrality in headphone reproduction, as in the case of Kunstkopf reproduction; all seven headphones were therefore adapted for free-field and diffuse-field reproduction by means of circuits designed on the basis of the results of the measurements shown in *Fig. 8*. During the listening tests, the test subject could choose among three matching characteristics : either of these two adaptations or no equalisation at all. Only one set of headphones was used during any single session.

The test material was carefully selected during preliminary trials. 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 sound mixers over the last 20 years, thereby ensuring that the test results would not be influenced by a tonal reproduction peculiar to any sound mixer.

Twenty-four test subjects participated in the listening tests. The majority were people employed in broadcasting (including four sound mixers) and practised in assessing transmission quality. For each set of headphones and each test sample, a preference had to be stated for one of the three tonal reproductions (one of the 3 possible corrections), first using the assessment categories " naturalness " and then that of " pleasantness ". These two criteria have shown themselves to be particularly significant in various quality rating tests on loudspeakers and headphones.

The results of the listening tests are shown in *Fig. 9*. The average values and areas of confidence are given for all nine programme samples separately, for the assessment " more natural " and " more pleasant ". It can be seen that with almost all headphones there was a significant preference for diffuse-field adaptation - the significance was lower only for headphones 7 and 3 in the " pleasant " category.

The statistical distributions of the opinions vary depending on the original transfer functions of the various headphones. The divergence in appreciation

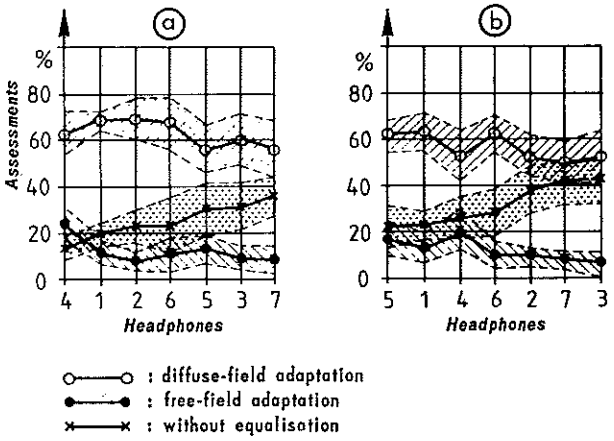

Fig. 9. — Overall quality assessment of headphones :
(a) natural character,
(b) pleasant listening.

is particularly small in the case of headphone 7 (STAX-SR-Lambda) without equalisation and with diffuse-field adaptation. This corroborates the good concordance between the original transfer function and the clearly optimal diffuse-field transfer function *(Fig. 8)*.

As was expected, the free-field transfer functions are distinctly less satisfactory than the corresponding diffuse-field functions, but only slightly less satisfactory than the position without equalisation, particularly for headphones 4 (HD 430) and 1 (DT 440). The overall results further indicate that diffuse-field adaptation ensures especially natural reproduction, but this does not imply a particularly pleasant coloration in the case of headphones 2, 3, 4 and 7, for which the manufacturers clearly produced a tonal reproduction tailored to a specific taste and given programme material.

Figs. 10 and *11* permit finer analysis to be made. They show in detail that in a few isolated cases diffuse-field adapted headphones provided a less-pleasant tonal reproduction than when the equalisation intended by the manufacturer is used. Nevertheless, these exceptional cases in no way affect the general superiority of diffuse-field adaptation.

It was further demonstrated that there is only a small range of variation in the tonal reproduction of the various headphones with standard diffuse-field adaptation. The coloration produced by headphones of quite different design was surprisingly similar. The relatively high price difference, for example between the STAX-SR-Lambda and the DT 880, scarcely seems to be justified.

5. Conclusions

Theoretical conceptions of the function of hearing in spatial listening have been expanded and described with the aid of the association model. The new knowledge so derived regarding optimum headphone equalisation may be summarised as follows.

Standardised adaptation of headphones for free-field reproduction is in principle the wrong equalisation for reproduction of intensity stereo. Reference to a free sound field basically fails to provide a satisfactory tonal

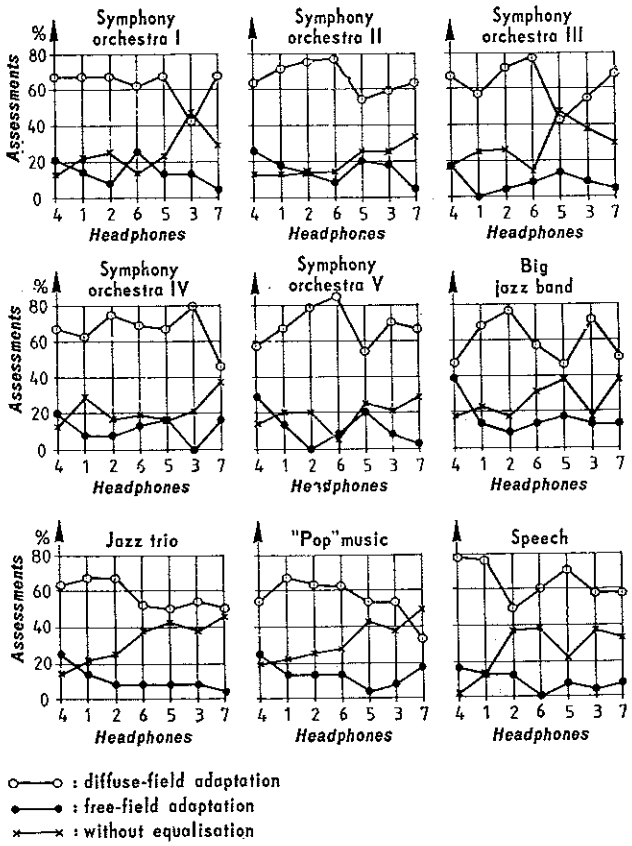

Fig. 10. — Assessment of the natural character of headphone reproduction.

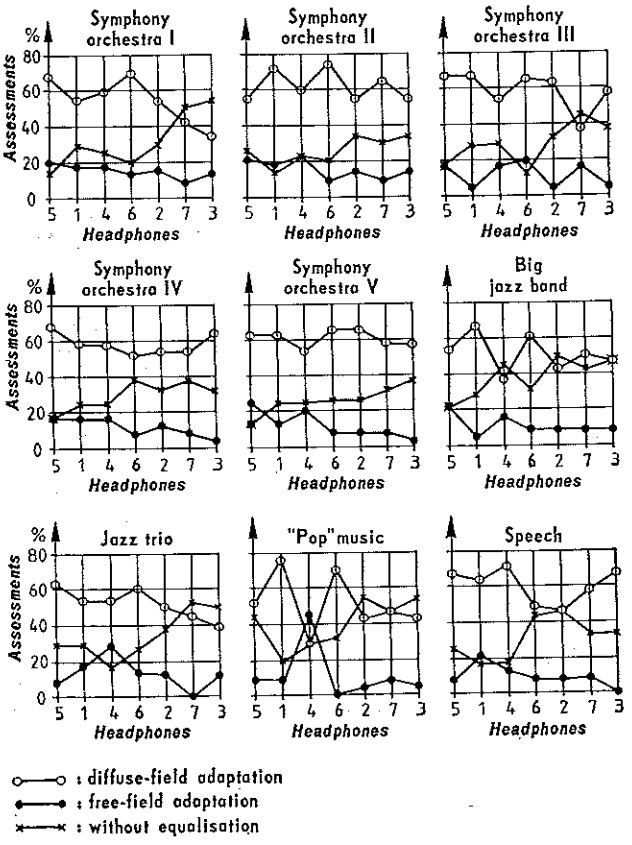

Fig. 11. — Assessment of the pleasant listening of headphone reproduction.

impression. Admittedly, the transfer function of the headphones is deduced from the directivity of the outer ear in a free sound field, but representation is much too inaccurate in comparison with the spectral features which the ear could actually exploit in the localisation process. If such accuracy were sufficient, the localisation process would operate for a monophonic signal and the listening event would occur outside the head. However, in that case the tonal impression would be as poor as that of a loudspeaker in a non-reflecting area. Furthermore, localisation outside the head is impossible even in theoretical terms in the reproduction of intensity stereo signals ; the directive auditory characteristics of the signals reproduced by the headphones cannot be " calculated ". That means, however, that a uniform free-field transfer function gives rise to coloration defects which considerably impair tonal reproduction.

The basis for equalisation of headphones cannot be any single reference apparatus ; the whole range of transfer functions of the outer ear must be replaced by a corresponding average transfer function. This is achieved by taking as the reference the diffuse sound field. Quality rating tests on headphones have shown that diffuse-field adaptation (i.e. a uniform diffuse-field transfer function) provides the optimum tonal reproduction.

Loudness measurements in accordance with DIN 45 619 and IEC Publication 268-7 produce erroneous results. Loudness comparison is correct only if the sound events being compared display identical spatial features. However, it can for instance be shown that a loudspeaker signal perceived as having the same intensity as a corresponding headphone signal causes a sound pressure level in the auditory canal which is 7.5 to 14 dB lower than the headphone signal. The difference depends on frequency, location of the loudspeaker and the test signal. Loudness is not totally determined by sound pressure in the auditory canal.

Measurements made using a probe deviate considerably from loudness measurements, especially at frequencies over 1.6 kHz. The cause probably lies in the ability of hearing to exploit specific spectral features of ear-signals, either for localisation or for coloration. As, in standardised loudness comparison, hearing events are not situated in the same place and the localisation process of the ear cannot be reliably eliminated, the basis taken for headphone measurements should be the physically-measurable auditory signal spectrum and not the evaluation of the spectrum, which is conditioned by the localisation process. Measurements with probes are easier and quicker to carry out than loudness measurements. They require fewer test subjects; in certain cases a typical test subject may be taken to function as an optimum " match " for all measurements. The typical human outer ear may conceivably be replaced in the future by an artificial reproduction.

The diffuse-field transfer function of headphones does not have to be measured in an echo-chamber. If the free-field transfer function of the headphones is still determined, but by means of measurements made using a probe, this can then be readily transposed in quantitative terms into the diffuse-field transfer function of headphones by means of the " focussing factor "

(0^0 - free-field transfer function minus diffuse-field transfer function) of the outer ear.

It is proposed that national and international standards be prepared for high-quality headphones. In contrast to current standards, which provide for a uniform free-field transfer function and loudness comparison measurements and permit broad tolerances, the standard for high-quality headphones should lay down a uniform diffuse-field transfer function and measurements made using a probe at the (typical) outer ear. This stipulation guarantees optimum tonal neutrality, thus considerably tightening the range of tolerance.

Such a provision, involving physical measurements, could then be used to lay down minimum requirements for studio headphones ensuring a sufficiently uniform sound picture, as in the case of microphones and loudspeakers. Subjective quality assessment of headphone listening to radio broadcasting would thus be adequately defined and should therefore be incorporated into CCIR Recommendation 562.

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