TECHNICAL REPORT

Physical characteristics of headphones used in psychophysical experiments

Tatsuya Hirahara*

*NTT Communication Science Laboratories, NTT Corporation,
3-1, Morinosato Wakamiya, Atsugi, 243-0198 Japan*

(Received 29 August 2003, Accepted for publication 10 November 2003)

Abstract: The IEC coupler, dummy-head and actual-ear responses, harmonic distortion, impulse response decay, phase rotation and group delay, external sound radiation, sound attenuation and acoustic crosstalk characteristics of six models of headphones, the TDH39, DT48, HD250 Linear II, HD414 Classic, HDA 200 and SR-Lambda Professional, are measured and compared. The results indicate that coupler responses and dummy-head responses are not identical to actual-ear responses in most models, open-air type headphones have poor sound shielding ability, and the harmonic distortion and phase characteristics of all headphones tested are not problematic.

Keywords: Headphone frequency response, Headphone calibration, Psychoacoustical experiments

PACS number: 43.38.Si, 43.66.Yw [DOI: 10.1250/ast.25.276]

1. INTRODUCTION

Psychoacoustical experiments or listening tests require at least three systems: A signal generator (stimulus-reproduction system), an audio amplifier (stimulus-transmission system), and an electro-acoustic transducer. Recent progress in electronics has reduced the number of problems associated with signal generators and audio amplifiers. As long as signals are in the audible range (20 Hz to 20 kHz) the physical characteristics of signal generators, such as a PC with D/A converters, and audio amplifiers are satisfactory. It is not so difficult to find audio equipment that has a fairly flat frequency response, low distortion, negligible crosstalk, no wow-flutter and stable gain. In contrast, problems still remain with electro-acoustic transducers and attempts at improvement are on going.

In most psychoacoustical experiments or listening tests, acoustic stimuli are usually presented to subjects through headphones. It is the headphone characteristics that determine whether the intended acoustic stimuli are presented to a subject or not. Each research group, however, has its own headphone preferences and sometimes presents results of studies without specifying headphones used. When acoustic stimuli have a narrow band spectrum, the sound pressure level of the stimuli frequency is crucial. For example, the headphone characteristics do not affect the subjects' performance in frequency discrim-

ination tests [1]. On the other hand, the headphone frequency response affects the estimation of the loudness of broadband signal [2] and the estimation of critical bandwidths [3].

This article evaluates the physical characteristics of the various types of headphones commonly used in psychoacoustical experiments.

2. HEADPHONE REQUIREMENTS IN PSYCHOACOUSTICAL EXPERIMENTS

An ideal headphone for psychoacoustical experiments should fulfill the following requirements. Firstly, so that acoustic stimuli are presented to a subject as intended, the actual-ear frequency response should be flat, distortions should be low, group delay characteristics should be flat, dynamic range should be wide enough and acoustic crosstalk should be small. Secondly, to ensure experiments are reproducible and reliable, headphone driver variability should be small, wearing variability and inter-subject variability should be small, headphone drivers should be physically and electrically tough and should have small secular variation and headphones should be supplied in the market stably. Further, headphones should fit on the subjects' head comfortably.

Unfortunately, none of the headphones fulfill all the requirements. In particular, the frequency response of all headphones is not flat even for the audible range. They have a band-pass response in general. Experimenters use any available headphone with the knowledge of its non-flat frequency characteristics. Further, it should be noted that

*Current affiliation: ATR Human Information Science Laboratories,
e-mail: hirahara@atr.jp

Fig. 1 Block diagram of the system for headphone characteristics measurement. Signals are generated and analyzed by an audio analyzer (Brüel & Kjær 2012). The headphone amplifier for dynamic headphones is HAC-94C (NOE). The SRM1/MkII Pro. (STAX) is used for SR-Lambda Professional. A custom-made artificial head, on which two IEC couplers are placed vertically spaced at 13.5 cm, is used to measure coupler responses. A head and torso simulator (Brüel & Kjær, 4128) with ear simulators (Brüel & Kjær, 4158) is used to measure dummy-head responses. A probe microphone (Etymotic Research, ER7C) placed in the concha is used to measure actual-ear responses.

some headphones show quite different coupler and actual-ear responses [4–18].

3. METHOD

3.1. Headphones

Six models of headphones were tested; the TDH39 (Telephonics), the DT48 (Bayer Dynamics), the HD250 Linear II (Sennheiser), the HDA200 (Sennheiser), the HD414 Classic (Sennheiser) and the SR-Lambda Professional (STAX). The TDH39 is a dynamic closed-air headphone with supraaural cushions, which is originally designed for use with audiometer. The DT48 is a dynamic closed-air headphone with circumaural cushions, which is originally designed for use with studio monitors. The HD250 Linear II is a dynamic closed-air headphone with circumaural cushions, which is designed for general use. The HDA200 is a dynamic closed-air headphone with circumaural cushions, which is designed for use with audiometers. The HD 414 Classic is a dynamic open-air headphone with supraaural cushions, which is designed for general use. It was re-introduced in 1995. The SR-Lambda Professional is a condenser open-air headphone with circumaural cushions, which is originally designed for music listeners. These headphones have been popularly used among psychoacousticians.

3.2. Measurement Setup and Procedure

Physical characteristics of the headphones were measured using IEC couplers (Brüel & Kjær 4153), a dummy head with ear simulators (Brüel & Kjær, 4128), and actual

ears. Block diagram of the measurement setup is shown in Fig. 1.

An audio analyzer (Brüel & Kjær, 2012) was used as signal generator and data analyzer. The steady state response (SSR) mode of the audio analyzer was used to measure frequency response, harmonic distortion level, sound attenuation characteristics, sound radiation characteristics and acoustic crosstalk level. In the SSR mode, a steady state transfer function is measured using stepped sine excitation. The time selective response (TSR) mode of the audio analyzer was used to measure phase response, group delay response and impulse decay response. In the TSR mode, a time-selective transfer function is measured using a linear continuous sine sweep with constant amplitude. As headphone amplifiers, the SRM1/MK2 Professional (STAX), whose volume control was replaced with a step attenuator, was used for SR-Lambda Professional, and the HA-94C (NOE) [19] was used for the other headphones. The input level of headphones was set so that the output sound pressure level for a 1-kHz tone was 70 dB SPL. EIAJ (Electronic Industries Association of Japan) standards define the input level for a headphone measurement to be one that gives 94-dB SPL output for 1-kHz signal. It is, however, rare to use 94 dB SPL stimuli in psychoacoustic experiments. A 70-dB SPL output level was chosen in consideration of the measurement of actual-ear responses.

The coupler responses were measured with an artificial head as shown Fig. 2, in which two IEC couplers were placed vertically with a spacing equivalent to that between

Fig. 2 The custom-made artificial head used to measure coupler responses.

ears [7,20,21]. Headphone cushions were received by two adapter plates (diameter of 21 cm) attached to each IEC couplers. The distance between the two adapter plates was adjustable from 12 to 18 cm. The distance between the headband and center of the IEC couplers, i.e. center of the headphone drivers, was adjustable from 10 to 16 cm. During the measurements, spacing between the two adapter plates was set at 13.5 cm and distance between the headband and center of the IEC couplers was set at 14.3 cm. These values were the mean values of four adult female subjects. Using this artificial head, lateral pressure of tested headphones was set similar to that when headphones are placed over the actual ears.

When dummy head responses were measured, silicone pinnae equipped with the head and torso simulator (Brüel & Kjær, 4128) were attached to the dummy head. As the silicone pinnae are stiffer than actual pinnae, air gaps between cushions and pinnae are formed when supraaural cushions are used.

When actual-ear responses were measured, a probe tube (silicon rubber, 0.95-mm outer diameter, 0.5-mm inner diameter) of a probe microphone (Etymotic Research, ER7C) was placed at the center of the outer ear entrance. Frequency responses of the probe microphone itself were measured in an anechoic room beforehand, and then measured actual-ear headphone responses were compensated with it. Subjects were four adult females who do not wear glasses.

Fig. 3 Frequency responses of the TDH39. Upper thin curve: mean coupler response of four drivers; upper dashed curve: mean dummy-head response of four drivers; upper thick curve: mean actual-ear response of one driver of two measurements for four subjects. Lower thin, dashed and thick curves are standard deviations of measured coupler, dummy-head and actual-ear responses.

Fig. 4 Frequency responses of the DT48. Upper thin curve: mean coupler response of ten drivers; upper dashed curve: mean dummy-head response of ten drivers; upper thick curve: mean actual-ear response of one driver for two measurements for four subjects. Lower thin, dashed and thick curves are standard deviations of measured coupler, dummy-head and actual-ear responses.

4. RESULTS

4.1. Frequency Response

Figures 3 to 8 show coupler, dummy-head and actual-ear responses for each headphone. With regard to coupler and dummy-head responses, the mean value and standard deviation of measured frequency responses of five sets of each model (two sets for TDH39), namely ten drivers (four drivers for TDH39) for each, are depicted. Thus, the

Fig. 5 Frequency responses of the HD250 Linear II. See captions of Fig. 3 for an explanation of the curves.

Fig. 6 Frequency responses of the HDA200. See captions of Fig. 3 for an explanation of the curves.

Fig. 7 Frequency responses of the HD414 Classic. See captions of Fig. 3 for an explanation of the curves.

Fig. 8 Frequency responses of the SR-Lambda Professional. See captions of Fig. 3 for an explanation of the curves.

standard deviation of coupler and dummy-head responses indicates inter-driver variations. With regard to actual-ear responses, the mean value and standard deviation of measured frequency responses of one driver of each model for two discrete measurements with the four subjects are depicted. Thus, the standard deviation of actual-ear responses indicates inter-subject and re-wearing variations.

The TDH39 shows quite different coupler, dummy-

head and actual-ear responses (Fig. 3). Although the coupler response is flat between 200 Hz to 1.5 kHz, the actual-ear response gradually tails off at low frequency. The dummy-head response abruptly declines below 1 kHz. The maximum standard deviation of the coupler response between 100 Hz and 5 kHz is 8 dB and that of the dummy-head response is 10 dB, while that of the actual-ear response is lower than 3 dB.

The DT48 also shows large differences in its coupler, dummy-head and actual-ear responses at low frequency regions (Fig. 4). The actual-ear response is much lower than the coupler response below 400 Hz and above 5 kHz. The dummy-head response is lower than the actual-ear response below 1 kHz. The maximum standard deviation of the coupler response between 100 Hz and 5 kHz is below 1.5 dB, while that of the dummy-head and actual-ear responses reaches 8 dB.

The HD250 Linear II also shows large differences among the responses at low and high frequency regions (Fig. 5). The origin of the dip around 250 Hz in the coupler and actual-ear responses is unknown. The maximum standard deviation of the coupler response between 100 Hz and 5 kHz is less than 2.5 dB, while that of the dummy-head reaches 8 dB. That of the actual-ear response is less than 4.5 dB.

The HDA200 also shows small difference among the responses below 1.5 kHz (Fig. 6). The actual-ear response suddenly drops above 5 kHz and the dummy-head response drops above 10 kHz, while the coupler response keeps flat. The maximum standard deviations of the responses between 100 Hz and 5 kHz are less than 2 dB.

The HD414 Classic shows small difference among the responses (Fig. 7). All the response is flat between 100 Hz to 1 kHz and shows a peak of about 5 dB to 11 dB in the region of 3 kHz. The dummy-head response is lower than the others below 100 Hz. The maximum standard deviation of the coupler and dummy-ear responses between 100 Hz and 5 kHz is less than 1.5 dB, while that of the actual-ear response reaches 4.5 dB at 2 kHz.

The SR-Lambda Professional shows fairly flat frequency response across a broad band (Fig. 8). The coupler and actual-ear responses show a dip of about 10 dB in the region of 3 to 4 kHz, while the dummy-head response does not. Differences between the coupler response and actual-ear response between 200 Hz to 5 kHz are small. The dummy-head response is almost identical with the coupler response up to 1 kHz. The standard deviations of the responses between 100 Hz and 5 kHz are less than 2 dB.

4.2. Harmonic Distortion

Harmonic distortion characteristics of the six models of headphones are depicted in Fig. 9. In this measurement, headphones were set on the coupler and the input level was

set to produce 100 dB SPL at 1 kHz. The harmonic distortion level was calculated at each frequency as the power ratio of the sum of the 2nd to 5th harmonic components to the fundamental component. For all headphones, harmonic distortion is less than -60 dB (i.e. less than 0.1% in amplitude ratio) between 100 Hz and 5 kHz.

4.3. Phase Rotation and Group Delay

Phase rotation and group delay characteristics of the six models of headphones are depicted in Figs. 10 and 11. The headphones were set on the coupler and responses were measured in the TSR mode of the audio analyzer. Phase characteristics of each headphone are relatively smooth. Fluctuations of group delay are thus small above 200 Hz.

4.4. Impulse Response Decay

Impulse response decay characteristics of the six models of headphones are depicted in Fig. 12. The headphones were set on the coupler and responses were measured in the TSR mode of the audio analyzer. Results show that the impulse response of each headphone decays -40 dB in a few milliseconds.

4.5. External Sound Radiation

External sound radiation characteristics of the five models of the headphones are depicted in Fig. 13. The external sound radiation level is defined as the ratio of the sound pressure level $P_{OUT}(f)$ measured at one meter from a headphone worn on a dummy head to the sound pressure level $P_{DH}(f)$ measured by the dummy head when a f Hz tone is produced by the headphone. This measurement was done in an anechoic room and P_{DH} (1 kHz) was set at 100 dB SPL.

The sound radiation level of HDA200 is less than -70 dB; those of DT48 and HD250 Linear II are less than -50 dB. In contrast, the sound radiation level of HD414 Classic is more than -55 dB between 1 k to 8 kHz; that of SR-Lambda Professional is more than -40 dB above 2 kHz. Namely, sound pressure level at one meter from SR-Lambda Professional is 30 dB SPL when 70 dB SPL sound is produced at an ear.

The TDH 39 was not measured because the air gaps between the supraaural cushion and stiff silicone pinna of the dummy head are large, which should produce a large amount of sound leak.

4.6. Sound Attenuation

Sound attenuation characteristics of the five models of headphones are depicted in Fig. 14. The sound attenuation level is defined as the ratio of sound pressure levels measured by the dummy head wearing and not wearing headphones, $P_{DHW}(f)/P_{DHO}(f)$. $P_{DHW}(f)$ is the sound pressure level with headphones and $P_{DHO}(f)$ is the sound

Fig. 9 Harmonic distortion characteristics (power ratio of sum of the 2nd to 5th harmonic distortion components to the fundamental component) of the six models of headphones measured with the IEC coupler.

Fig. 10 Phase characteristics of the six models of headphones measured with the IEC coupler.

pressure level without headphones when a f Hz tone is produced by a loud speaker placed at one meter from the dummy head. This measurement was done in an anechoic room and P_{DHO} (1 kHz) was set at 90 dB SPL. All headphones except the HD414 Classic and SR-Lambda Professional exhibits 10-dB to 15-dB sound attenuation at high frequency. These headphones, therefore, can insulate sound somewhat. In contrast, sound attenuation of the HD414 Classic and SR-Lambda Professional is almost 0 dB for wide frequency range. These headphones are almost transparent to sound.

The TDH39 was not measured because of the air gaps

Fig. 11 Group delay characteristics of the six models of headphones measured with the IEC coupler.

Fig. 12 Impulse response decay characteristics of the six models of headphones measured with the IEC coupler.

between the cushion and silicone pinna. Arlinger reported the sound attenuation characteristics of the TDH39 with cushion MX-41/AR using the hearing threshold method [22]. According to his measurement, the maximum sound attenuation of the TDH39 was 28.3 dB at 4 kHz.

4.7. Acoustic Crosstalk

Acoustic crosstalk characteristics of the HDA200 and SR-Lambda Professional are depicted in Fig. 15. The acoustic crosstalk level is defined as the ratio of sound pressure level $P_{Left}(f)$ measured by a probe microphone (Etymotic Research, ER7C) at the left ear to that at the right ear $P_{Right}(f)$ when a f Hz tone is given at the right ear by a headphone. This measurement was done in an anechoic room for four subjects' ears. Mean values of

Fig. 13 External sound radiation characteristics of the five models of headphones.

Fig. 14 Sound attenuation characteristics of the five models of headphones.

$P_{\text{Left}}(f)/P_{\text{Right}}(f)$ for the four subjects are shown in Fig. 15.

With regard to the HDA200, although acoustic crosstalk at low frequency is relatively large, 50 dB or more attenuation can be expected between right and left ears between 300 Hz to 5 kHz. On the other hand, the acoustic crosstalk level of the SR-Lambda Professional is only -30 to -40 dB at 2 to 3 kHz, where the hearing threshold is low.

5. DISCUSSIONS

The TDH39, DT48, HD250 Linear II and HDA200 are closed-air type headphones, which produce sound pressure in a small cavity formed by a close contact of the headphone cushion and the pinna or head. When a

Fig. 15 Acoustic crosstalk characteristics of the HDA 200 and SR-Lambda Professional.

Fig. 16 Acoustic equivalent circuit for a headphone, including the acoustic leak path.

headphone is placed on an adapter plate of an IEC coupler, the cushion and the adapter plate contact closely. In contrast, when a headphone is worn by subjects, air gaps often form between the cushion and head because the pinna and hair prevent a tight seal between them. This happens even more so for those who wear glasses.

These air gaps are represented as an acoustic resistance of leak (R_{Leak}) and an acoustic mass of leak (M_{Leak}) in the equivalent circuit of a headphone shown in Fig. 16. As acoustic impedance of coupling cavity (Z_C) is capacitive, frequency response at low frequency deteriorates when the internal acoustic impedance of a headphone (Z_0) is high [23,24]. The sizes of air gaps, which alter actual-ear response a lot, vary a lot depending on a shape and materials of the cushion. Thus, actual-ear response can be improved by contriving the shape and materials of the cushion [17,25,26].

As shown in Figs. 3 to 5, dummy-head responses are lower than actual-ear responses and actual-ear responses are lower than coupler responses at low frequency for the TDH39, DT48 and HD250 Linear II. These differences come from air gaps formed by breaks in the seal between the cushion and the head.

On the other hand, as shown in Fig. 6, the dummy-head response is much lower than the actual-ear response but the difference between actual-ear and coupler responses is small for the HDA200. This is because the cushion contacts the head very closely so few air gaps are formed. When the HDA200 is put above the adapter plate of the IEC coupler by inserting two plastic rods (8 mm diameter) between the cushion and the adapter plate, the coupler response at low frequency deteriorates severely as shown in Fig. 17. This “open-coupling” coupler response is similar to the dummy-head response. This suggests that the air-gap situation of the HDA200 worn on the dummy head is similar to that of the “open-coupling” with the IEC coupler.

The HD414 Classic is an open-air type headphone. Its ear cushion is made of soft urethane foam. The cushion is sandwiched between the headphone driver and pinna when the headphone is worn. The seal between the cushion and the pinna can not be expected and there are air gaps. This situation is similar for the coupler and dummy-head measurements. The difference among coupler, dummy-head and actual-ear response is small just because the air gap situation for the coupler, dummy-head and actual-ears

Fig. 17 Frequency responses of the HDA 200. Thin curve: normal coupler response of the HDA200 driver (normal coupling); thick curve: coupler response of the same driver when the driver was put above an adapter plate by inserting two plastic rods (8 mm ϕ) between the cushion and the adapter plate (open coupling).

might be the same.

The SR-Lambda Professional is another open-air type headphone. It is called an ear speaker because a small condenser speaker is located at the listener's ear. The cushion of the SR-Lambda Professional is not flat to assure better fitting to the head. Thus, when the SR-Lambda Professional is placed on the flat adapter plate of the IEC coupler, air gaps are formed. In contrast to the other headphones tested, the coupler response at low frequency is lower than the actual-ear response. When the cushion of an SR-Lambda Professional and adapter plate are completely air sealed by packing tape, a resonance around 100 Hz moves down to 40 Hz and the frequency response at low frequency is improved. On the other hand, when the seal between cushion and adapter plate is removed and two plastic rods are inserted between them, a resonance around 100 Hz moves up to 200 Hz and frequency response at low frequency deteriorates as shown in Fig. 18. These results indicate that the acoustic load of the open-air type headphone affects the frequency response at low frequency. As there are small differences between the actual-ear response and coupler response, the SR-Lambda Professional is seemingly not affected by the acoustic load variation. However, the responses are similar as seen in Fig. 8 just because the air gap situation for the coupler, dummy-head

Fig. 18 Frequency responses of the SR-Lambda Professional. Thin curve: normal coupler response of the SR-Lambda Professional driver (normal coupling); thick curve: coupler response of the same driver when the driver was put above an adapter plate by inserting two plastic rods (8 mm ϕ) between the cushion and the adapter plate; thick gray curve (open coupling): coupler response of the same driver when the cushion and adapter plate were completely sealed by packing tape (completely air-sealed).

and actual-ears might be the same.

For all of the headphones, differences between the actual-ear and the coupler response are large above 5 kHz. These differences are most likely caused by acoustic reflection at the adapter plate and the acoustic load differences between an actual ear and an artificial ear.

One way to make the actual-ear response flat is to insert an electronic equalizer between the signal generator and headphone. Namely, by measuring the actual-ear response of the headphone each time a subject wears it before an experiment, we can design a linear phase digital filter that has inverse characteristics of the actual-ear response. Then, stimuli are presented to subjects via a real-time convolution system that performs the inverse filtering. Another method is to prepare equalized stimuli in advance. Inverse filter design using mean actual-ear responses is effective for the SR-Lambda Professional and HDA200, both of which have small inter-driver and inter-subject differences in frequency response [27].

All of the headphones seem to have small harmonics distortion and acceptable phase and group delay characteristics. Hirahara *et al.* [28] reported that intermodulation distortion of headphones is small enough.

The SR-Lambda Professional and the HD414 Classic are almost transparent to sounds. Even when they are worn, outside sounds reach listener's ear and the produced sound is radiated outside. Accordingly, one subject can hear stimuli presented to another when multiple subjects sit next to one another and different stimuli are simultaneously presented to them. The subjects preferred to use circumaural headphones that have better sound attenuation characteristics, such as the DT48 or the HDA200. They reported that they could concentrate on the sound stimuli even when experiments were carried out in a quiet soundproof room (noise floor: 25 dBA).

Møller [29] has reported that the acoustic impedance of a headphone should have the same free-air radiation impedance seen from the ear canal in order to reproduce binaural signal via headphones. The SR-Lambda Professional satisfies this criterion [30], so it is often used in binaural experiments. The SR-Lambda Professional, however, does not assure separation of the two channels. If you are using the SR-Lambda Professional, it should be taken into account that the sound presented at one ear is reaching the other ear.

6. CONCLUSION

The physical characteristics of six models of headphone used in psychoacoustical experiments were investigated. First of all, it was reconfirmed that coupler and dummy-head responses are not identical to actual-ear responses in most models. Secondly, it became also apparent that an open-air type headphone has poor sound

shielding ability. Produced sounds are radiated to the outside and thus acoustic crosstalk occurs. It was shown that the harmonic distortion and phase characteristics of all headphones tested were not problematic.

This investigation has not necessarily dealt with all of the physical characteristics required for headphones used in psychoacoustical experiments. For example, the acoustic impedance required for binaural experiments mentioned in section 5 remains to be examined. Investigating insert type earphones such as the ER-3A and ER-4S (Etymotic Research) also remains as the future work. Killion *et al.* [12] has reported that an insert earphone demonstrates advantages over supraaural headphones.

Another method of measuring headphone frequency responses is loudness comparison. Subjects adjust the "headphone loudness" of narrow-band test signals by based on comparison with a reference sound pressure level in a free field [14]. Results for several headphones are published [2,31,32]. Such measurement for the HDA200 is an issue in the future.

In most physiological experiments, the frequency response of the acoustic system is calibrated and digitally equalized. An experimenter confirms whether the equalization works or not before and after the experiment [33,34]. In contrast, equalization of the acoustic system seems to be rarely done in psychoacoustical experiments. Experimenters should pay more attention to the actual-ear response of a headphone so that the intended acoustic stimuli are presented to subjects when the stimuli have broad band spectrum.

REFERENCES

- [1] C. C. Wier, W. Jesteadt and D. M. Green, "Frequency discrimination as a function of frequency and sensation level," *J. Acoust. Soc. Am.*, **61**, 178–184 (1977).
- [2] H. Fastl, S. Namba and S. Kuwano, "Freefield response of the headphone Yamaha HP1000 and its application in the Japanese round robin test on impulsive sound," *Acustica*, **58**, 183–185 (1985).
- [3] H. Fastl and E. Schorer, "Critical Bandwidth at low frequencies reconsidered," in *Auditory Frequency Selectivity*, B. C. J. Moore and R. D. Patterson, Eds. (Plenum, New York, 1986), pp. 311–322.
- [4] Z. Yamaguchi and N. Sushi, "Real ear response of receivers," *J. Acoust. Soc. Jpn. (E)*, **12**, 8–13 (1956).
- [5] E. Kawaguchi, M. Yamamoto and T. Komoda, "Response testing of circumaural and supraaural earphones," *Proc. Autumn Meet. Acoust. Soc. Jpn.*, pp. 69–70 (1967).
- [6] M. Yamamoto, E. Kawaguchi and T. Komoda, "Response testing of circumaural and supraaural earphones," *Proc. Autumn Meet. Acoust. Soc. Jpn.*, pp. 277–278 (1969).
- [7] S. Yamamoto, E. Kawaguchi and T. Komoda, "Artificial ear for circumaural earphones," *Acustica*, **24**, 42–49 (1971).
- [8] I. Ebihara, Y. Ase, S. Li and Y. Koizumi, "Basic studies of 'OPEN-AIR' type earphone (HD414) for its clinical use," *Proc. Spring Meet. Acoust. Soc. Jpn.*, Vol. 1, pp. 135–136 (1974).

- [9] H. Fastl, "Comparison of DT48, TDH49 and TDH39 earphones," *J. Acoust. Soc. Am.*, **66**, 702–703 (1979).
- [10] R. M. Cox, "MBS-9A coupler to eardrum transformation: TDH-39 and TDH-49 earphone," *J. Acoust. Soc. Am.*, **79**, 120–123 (1986).
- [11] J. Zwislöck, J. D. Miller, A. F. Niemoeller, E. A. Shaw and G. Studebaker, "Earphones in audiometry," *J. Acoust. Soc. Am.*, **83**, 1688–1689 (1988).
- [12] M. C. Killion and E. Villchur, "Comments on 'Earphones in audiometry'," *J. Acoust. Soc. Am.*, **85**, 1775–1778 (1989).
- [13] T. Hirahara and K. Ueda, "A study on headphones suitable for psycho-acoustic experiments," *Proc. Autumn Meet. Acoust. Soc. Jpn.*, pp. 427–428 (1989).
- [14] I. Ohira, "Specification and methods of measurement on audio equipment (Part 3) —Headphones—," *J. Acoust. Soc. Jpn. (J)*, **45**, 556–564 (1989).
- [15] E. Zwicker and H. Fastl, *Psychoacoustics, Facts and Models* (Springer-Verlag, Berlin/Heidelberg, 1990), pp. 5–8.
- [16] K. Ueda and T. Hirahara, "Headphones as psychoacoustical experiment apparatus: Frequency response and impulse response," *Trans. Tech. Comm. Psychol. Physiol. Acoust.*, H-90-5 (1990).
- [17] M. Ogawa and U. Irii, "A study on standard receiver to use speech quality measurement for wide-band telephonometry," *Proc. Autumn Meet. Acoust. Soc. Jpn.*, Vol. 1, pp. 417–418 (1990).
- [18] H. Takeshima, T. Hiraoka, M. Kumagai, Y. Suzuki and T. Sone, "On the measurement of reference equivalent threshold sound pressure levels for the audiometer earphone," *Trans. Tech. Comm. Psychol. Physiol. Acoust.*, H-94-46 (1994).
- [19] T. Hirahara, "Headphone amplifier for psychoacoustic experiments," *ATR Tech. Rep.*, TR-A-0034 (1989).
- [20] H. Miura, K. Muto and T. Fujimori, "On a calibration of headphones by the IEC artificial ear mounted on an artificial head," *Trans. Tech. Comm. Psychol. Physiol. Acoust.*, H-82-52 (1982).
- [21] U. Richter, "A new coupler for circumaural earphones," *Audiol. Acoust.*, **25**, 210–228 (1986).
- [22] S. D. Arlinger, "Sound attenuation of TDH-39 earphones in a diffuse field of narrow-band noise," *J. Acoust. Soc. Am.*, **79**, 189–191 (1986).
- [23] A. Uchiumi, S. Noge and S. Yoshikawa, "Measurement of earphone response using the ear simulator," *Proc. Spring Meet. Acoust. Soc. Jpn.*, Vol. 1, pp. 405–406 (1990).
- [24] Y. Kajikawa, Y. Nomura and J. Ohga, "Possibility of reducing an effect of leak by an automatic design of telephone-handset using nonlinear optimization method," *J. Acoust. Soc. Jpn. (J)*, **51**, 349–357 (1995).
- [25] E. Villchur, "Audiometer-earphone mounting to improve intersubject and cushion-fit reliability," *J. Acoust. Soc. Am.*, **48**, 1387–1396 (1970).
- [26] R. P. Lippmann, "MX41/AR earphone cushions versus a new circumaural mounting," *J. Acoust. Soc. Am.*, **66**, 702–703 (1981).
- [27] T. Hirahara, "Reexamination of earphones suitable for psycho-acoustic experiments," *Tech. Rep. IEICE*, EA95-29 (1995).
- [28] T. Hirahara, S. Suzuki and K. Ueda, "Measurement of distortion product of headphones used in psychoacoustic experiments," *ATR Tech. Rep.*, TR-A-0082 (1990).
- [29] H. Møller, "Fundamentals of binaural technology," *Appl. Acoust.*, **36**, 171–218 (1992).
- [30] H. Møller, D. Hammershøi, C. B. Jensen and M. F. Sørensen, "Transfer characteristics of headphones measured on human ears," *J. Audio Eng. Soc.*, **43**, 203–217 (1995).
- [31] G. Theile, "On the standardization of the frequency response of high-quality studio headphones," *J. Audio Eng. Soc.*, **34**, 956–969 (1986).
- [32] K. Ueda and T. Hirahara, "Frequency response of headphones measured in free field and diffused field by loudness comparison," *J. Acoust. Soc. Jpn. (E)*, **12**, 131–138 (1991).
- [33] N. Y. S. Kiang, *Discharge Patterns of Single Fibers in the Cat's Auditory Nerve* (MIT Press, Cambridge, MA, 1965), pp. 4–7.
- [34] T. Hirahara, "The representation of sound in the auditory peripheral system," *J. Acoust. Soc. Jpn. (J)*, **51**, 565–571 (1995).