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Discrepancies between actual-ear and artificial-ear responses

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ABSTRACT

This paper aims at clarifying the discrepancies between actual-ear and artificial-ear responses. The actual- and artificial-ear responses from five models of insert earphones, three models of intra-concha earphones, and two models of headphones were measured and compared. The actual-ear responses were measured for one driver of each earphone/headphone with sixteen ears of eight subjects using a probe-tube microphone ER-7C (Etymotic Research). The artificial-ear responses are measured for four drivers of each earphone/headphone using a head and torso simulator (Brüel and Kjær, type 4128C) with a built-in ear-simulator (type 4158C) and a pinna simulator (DZ9763). The results indicate that the actual-ear responses of intra-concha earphones and headphones below 4–5 kHz coincide with the artificial-ear responses and that the actual-ear responses of all earphones and headphones between 6 to 10 kHz are lower by at least 6 dB than the artificial-ear responses. The actual-ear responses of insert earphones below 300 Hz were lower by at least 6 dB than the artificial-ear responses due to acoustic leaks. We highly recommend that earphones and headphones be calibrated before acoustical experiments are conducted, keeping in mind the discrepancies between actual-ear and artificial-ear responses.

INTRODUCTION

Frequency response is one of the most important acoustical characteristics of earphones, which transduce electrical signals to sound. Measuring the frequency responses of a loudspeaker is not too difficult, as it produces sound pressure in an open space. In contrast, measuring the frequency responses of an earphone is not as easy as one might think. This is because an earphone produces sound pressure in a small closed space, which is formed by the outer ear canal and the earphone plug or housing. The physical dimensions as well as acoustical characteristics of this closed space have to be taken into account in measuring earphone responses. The shapes and sizes of the outer ear canal, however, vary from one individual to another. The conditions under which an earphone is worn can also differ from one individual to another.

Devices used for measuring earphone responses are an artificial ears that are designed to have an overall acoustic impedance similar to that of the average human ear over a given frequency range. There are three types of artificial ears specified in IEC Publications.

The Type 1 artificial ear specified in IEC Publication 60318 is used for measurements on supra-aural and supra-concha earphones. The intended frequency range of the Type 1 artificial ear is that of the telephone bandwidth (100 Hz to 4 kHz). The sound pressure measured by the Type 1 artificial ear is referred to the ear reference point (ERP).

The Type 2 artificial ear specified in IEC Publication 60711 is an occluded-ear simulator for testing insert earphones. The intended frequency range of the Type 2 artificial ear is 100 Hz to 8 kHz. The sound pressure measured by the Type 2 artificial ear is referred to the ear-drum reference point (DRP).

The Type 3 artificial ear consists of the IEC 60711 occluded-ear simulator and a concha simulator or a pinna simulator. The intended frequency range of the Type 3 artificial ear is 100 Hz to 8 kHz. The Type 3.1 artificial ear has a concha bottom simulator. The Type 3.2 artificial ear has a simplified pinna simulator. It is used for measurements on supra-aural and supra-concha earphones. The sound pressure measured by the Type 3.2 artificial ear is referred to the ERP. The Type 3.3 artificial ear has the pinna simulator described in IEC Publication 60959. The Type 3.3 artificial ear can be used for measurements on supra-aural, supra-concha, intra-concha, and insert earphones. The sound pressure measured by the Type 3.3 artificial ear is referred to the DRP. The Type 3.4 artificial ear has a simplified (e.g. geometrically describable) pinna simulator. The Type 3.4 artificial ear can be applied to all types of earphones.

There are currently various types of earphones for portable solid-state audio players, as typified by iPod available on the market. Type 3 artificial ears, or IEC 60711 couplers, have been widely used to calibrate earphones. Even though its intended frequency range is 100 Hz to 8 kHz, frequency responses of up to 20 kHz or more are measured with artificial ears. I have also been using artificial ears to calibrate the earphones I have used in my psychoacoustical experiments, but have been a little anxious about their frequency-range limitations [2, 3].

This paper aims at clarifying the discrepancies between actual-ear and Type 3.3 artificial-ear responses by comparing these in various types of earphones.

METHOD

Earphones

Five models of insert earphones, three models of intra-concha earphones, and two models of "headphones" were tested. The specifications for the earphones are listed in Table 1.

The insert earphones tested were the E4C (Shure), ER4B (Etymotic Research), MDR-EX90SL (SONY), ATH-CK32 (Audio Technica) and SR-001MK2 (STAX). The E4C and ER4B use a balanced armature type sub-miniature speaker as a driver. The MDR-EX90SL and ATH-CK32 use a small dynamic speaker as a driver. The SR-001MK2 uses an electro-static driver. This earphone is mounted on a headband and its ear tip is pushed to the outer ear canal, resulting the outer ear canal being almost completely sealed. Thus, the SR-001MK2 is classified as an insert earphone in this article. These insert earphones are designed for consumer use.

The intra-concha earphones tested were the MX500 (Sennheiser), DNC2007 (manufacturing company is undisclosed) and TriPort IE (Bose). The DNC2007 is the earphone used for the English-listening-comprehension test held by the National Center Test for University Admissions in 2007 in Japan. All of these earphones use a small dynamic speaker as a driver. The MX500 and DNC207 are typical intra-concha earphones. The TriPort IE, however, is an intermediate between the insert and the intra-concha types. This is because the ear piece of the TriPort IE is partially inserted into the ear canal but it dose not seal the ear canal. Thus, the TriPort IE is classified as an intra-concha earphone in this article. The MX500 and TriPort IE are designed for consumer use.

The circum-aural earphone tested was the HDA200 (Sennheiser), which is a closed-type dynamic headphone for audiometric use. Another earphone tested was the K-1000 (AKG), which is an open-type dynamic headphone for consumer use. The K-1000 might be better classified as an "ear-speaker" rather than supra-aural type. This is because small loudspeakers are placed very close to the ears.

Measurement system and procedure

The artificial-ear responses were measured for the four drivers of each earphone using a head and torso simulator (Brüel and Kjær, type 4128C) with a built-in IEC60711 ear-simulator (type 4158C) and a pinna simulator (DZ9763).

The actual-ear responses were measured for one driver of each earphone with eight subjects using a probe-tube microphone ER-7C (Etymotic Research). The probe tube of the ER-7C, which was 72.5-mm long with an outer diameter of 0.95 mm, was carefully inserted into the ear canal and the end of the probe tube was placed very close to the subject's

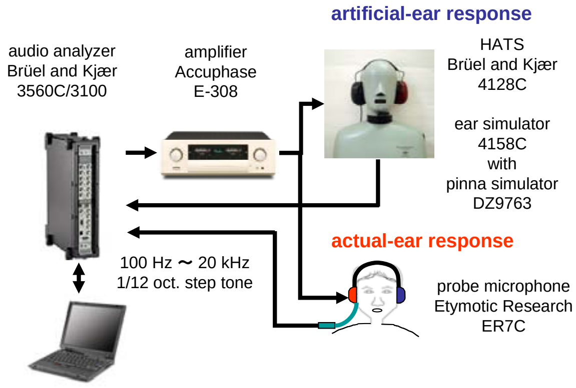

Figure 1. System for measuring earphone responses

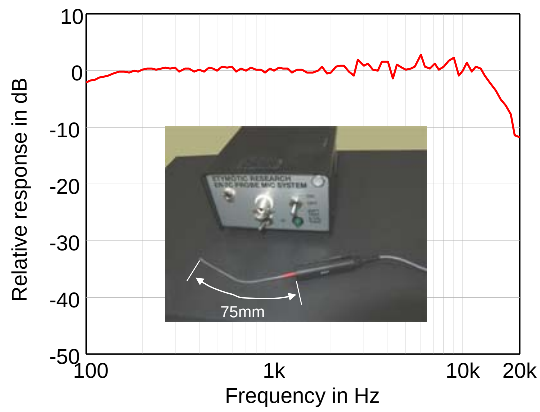

Figure 2. Free-field response of ER7C with probe tube

tympanic membrane. The exact position of the probe-tube tip in the outer-ear canal for each subject, however, was unknown. The mean insertion length of the probe tube from the entrance of the outer-ear canal for the eight subjects was 22.1 mm with a standard deviation of 4.4 mm. The frequency response of the ER7C with the probe tube was calibrated in a free field. The response of the ER7C in Figure 2 was subtracted when calculating the actual-ear response of each earphone.

A PULSE audio analyzer (Brüel & Kjær, type 3560C) with a wideband frontend module (type 3110) was used for signal generation, acquisition and data analysis. Frequency responses were measured from 100 Hz to 20 kHz in 1/12 octave steps using the steady state response (SSR) mode of the audio analyzer. The audio amplifier E-308 (Accuphase) was used as the driver amplifier for the earphones. The output sound pressure level of each earphone was set at 80 dB SPL for a 1- kHz tone by adjusting the amplifier gain. The measurements were carried out in a sound attenuated room.

Table 1. Specifications of the earphones (from the catalogues)

earphone type	model	manufacturer	transducer	bandwidth	sensitivity	impedance	weight
insert	E4C	Shure	electro magnetic	—	109 dB	29 Ω	31g
	ER4B	Etymotic Research	electro magnetic	20 Hz～16 kHz	98 dB	100 Ω	28 g
	MDR-EX90SL	SONY	dynamic	5 Hz～25 kHz	106 dB	16 Ω	7 g
	ATH-CK32	Audio Technica	electro magnetic	18 Hz～22 kHz	101 dB	16 Ω	5 g
	SR-001 MK2	STAX	electro static	20 Hz～20 kHz	111dB	360 kΩ/10 kHz	28 g
intra-concha	MX500	Sennheiser	dynamic	18 Hz～22 kHz	119 dB	32 Ω	6 g
	DNC2007	not disclosed	dynamic	—	—	—	—
	TriPort IE	Bose	dynamic	—	—	—	20 g
circum-aural	HDA200	Sennheiser	dynamic	20 Hz～20 kHz	100 dB	40 Ω	330 g
ear-speaker	K-1000	AKG	dynamic	30 Hz～25 kHz	74 dB	120 Ω	270 g

RESULTS

Figure 3 plots the actual-ear and artificial-ear responses for each earphone. The mean value and standard deviation of measured frequency responses of one driver of each model for four discrete measurements with the eight subjects for actual-ear responses are plotted by the blue line. Thus, the standard deviation of actual-ear responses indicates inter-subject and re-wearing variations. The mean value and standard deviation of measured frequency responses of two sets of each model (one set for K-1000), viz., four drivers (two drivers for K-1000) for each, for artificial-ear responses are plotted by the red line. Thus, the standard deviation of artificial-ear responses indicates inter-driver variations.

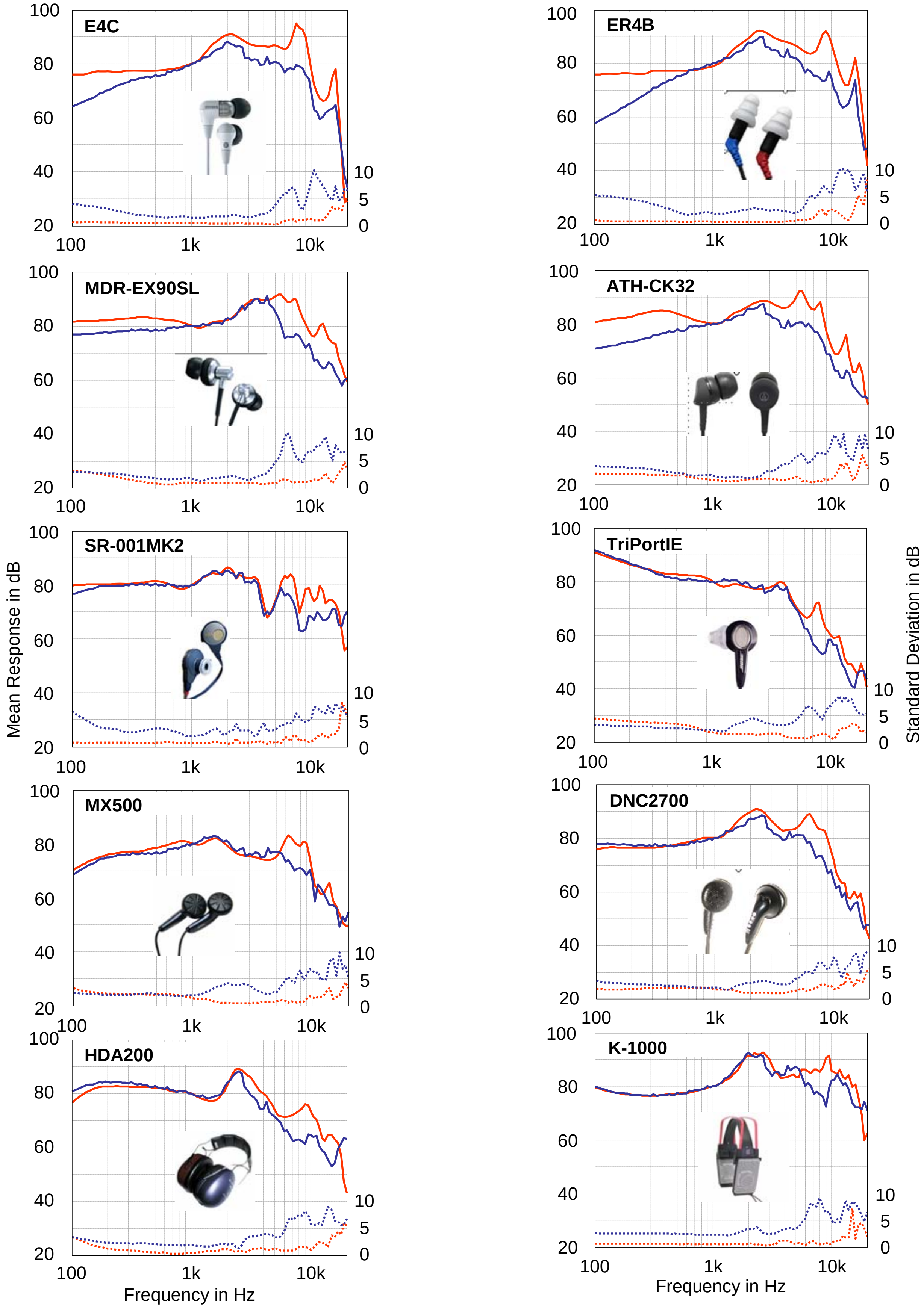

Figure 3. Actual-ear response (blue line) and artificial-ear response (red line) of each earphone.

The E4C and ER4B have large discrepancies between the actual-ear and artificial-ear responses below 300 Hz and above 3 kHz. The actual-ear responses are lower than those for the artificial ears in these frequency bands. The standard deviation of actual-ear responses is large for these earphones, suggesting large variations in inter-subject and re-wearing. In contrast, that of the artificial-ear response is almost 0 dB up to 10 kHz, suggesting inter-driver variations are small.

The MDR-EX80SL and ATH-CK32 also have discrepancies between the actual-ear and artificial-ear responses. The discrepancies are large above 6 kHz, while those at low frequency are small, in particular for the MDR-EX80SL. The standard deviation of the actual-ear responses is large above 5 kHz but is small below 2–3 kHz. The standard deviation of the artificial-ear responses is smaller than 3 dB below 10 kHz.

The SR-001MK2 has small discrepancies between the actual-ear and the artificial-ear responses below 5 kHz, yet has large discrepancies at high frequency. The standard deviation of the actual-ear responses is relatively larger than that of the other insert earphones. The standard deviation of the artificial-ear responses is very small.

The TriportIE also has small discrepancies between the actual-ear and artificial-ear responses below 5 kHz, yet has large discrepancies at high frequency. The standard deviation of the actual-ear responses is large in the higher-frequency region. The standard deviation of artificial-ear responses is large below 1 kHz.

The MX500 and DNC2007 have very small discrepancies between the actual-ear and artificial-ear responses below 4 kHz and above 10 kHz. The standard deviation of the actual-ear and artificial-ear responses is the same below 1 kHz, but that of the actual-ear responses is larger than that of the artificial-ear responses above 1 kHz.

The HDA200 has small discrepancies between the actual-ear and artificial-ear responses below 5 kHz. The standard deviation of the actual-ear responses is larger than that of the artificial-ear responses at any frequency.

The K-1000 has very small discrepancies between the actual-ear and artificial-ear responses below 6 kHz. The standard deviation of the actual-ear responses is larger than that of the artificial-ear responses at any frequency. The standard deviation of the artificial-ear responses is almost 0 dB up to 10 kHz.

Figure 4 plots the mean discrepancy between the actual-ear and artificial-ear responses of each earphone type in decibels. That is, the ratio of actual-ear responses to artificial-ear responses at each frequency was calculated for each earphone model, then the means of discrepancy functions were obtained by taking the mean of the ratio function for five insert earphones (red), three intra-concha earphones (green), and the other two earphones (blue), i.e. headphones.

The artificial-ear responses were higher at low frequencies below 600 Hz than the actual-ear responses in the insert earphones. The discrepancies were 6 dB or more below 300 Hz. In contrast, the artificial-ear responses were about the same as the actual-ear responses for intra-concha earphones and headphones below 2.5 kHz. The artificial-ear responses in the mid-frequency from 6 to 10 kHz were higher by at least 6 dB than the actual-ear responses for any type of earphone. The artificial-ear responses at frequencies above 10 kHz were higher by at least 6 dB than the actual-ear responses for any type of earphone. In particular, the actual-ear responses of insert earphones were much higher than the artificial-ear responses.

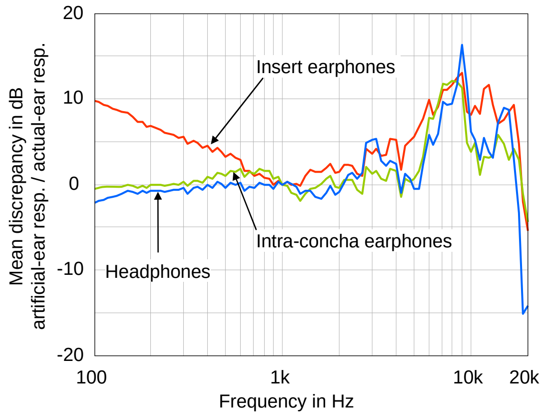

Figure 4. Mean discrepancy between actual- and artificial-ear responses for each type of earphone.

DISCUSSION

The Type 3.3 artificial-ear simulated the actual ear fairly well for the intra-concha earphones and headphones below 4–5 kHz. However, the discrepancies between the actual-ear and artificial-ear responses were large below 300 Hz for the insert earphones. The air gaps between the ear tips of the earphones and the outer-ear canal could be the cause of the lowered actual-ear responses at low frequency [2, 3]. The probe tube, whose diameter was 0.95 mm, was sandwiched between the ear tip and outer-ear canal wall, creating small air gaps. Such discrepancies were not seen for the MDE-EX80SL. The ear tip of the MDE-EX80SL was less stiff than that of the E4C, ER4B or ATH-CK32, sealing off the outer-ear canal more efficiently even when the probe tube was sandwiched between the earpiece and outer-ear-canal wall. The discrepancies between the actual-ear and artificial-ear responses were large between 6 to 10 kHz for all earphone types. The actual-ear responses were always higher by at least 6 dB than the Type 3.3 artificial-ear responses. The cause for this remains unknown. The discrepancies between the actual-ear and artificial-ear responses were also large above 10 kHz. This frequency range, however, is beyond the intended frequency range of the Type 3.3 artificial-ear.

CONCLUSION

The artificial-ear responses below 5–6 kHz were about the same as the actual-ear responses except for the insert earphones. The actual-ear responses of the insert earphones below 300 Hz were lower by 6 dB or more due to acoustic leaks. The artificial-ear responses of all type of earphones between 6 to 10 kHz were higher by at least 6 dB than the actual-ear responses. The discrepancies between the actual-ear and artificial-ear responses were large above 10 kHz. It is highly recommended that earphones be calibrated before acoustical experiments are conducted, keeping in mind the discrepancies between actual-ear and artificial-ear responses.

ACKNOWLEDGEMENT

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REFERENCES

1 IEC268-7 Second edition, Sound system equipment- Part 7: Headphones and earphones, (1996).
2 T.Hirahara,"Physical characteristics of headphones used in psychophysical experiments," *Acoustical Science and Technology* **25(4)**, 276-285 (2004).
3 T. Hirahara, H. Aoyama, and M. Otani. "Acoustic characteristics of earphones and issues of IEC60711 coupler," *J. Acoust. Soc. Jpn.* 66, 45-55 (2010). (in Japanese)