Errors in the measurements of individual headphone-to-ear-canal transfer function

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Introduction

In virtual auditory display via headphone, the unwanted spectral transformation (i.e., Headphone-to-ear-canal transfer functions, HpTFs) introduced by unflat headphone response and the acoustical coupling between the headphone transducer and the external ear should be eliminated in order to ensure authentic reproduction [1,2]. Since each person owns a unique dimension of external ear (especially pinna), HpTFs are individual-dependent. Acoustical measurement is a common way to obtain individual HpTFs. In practice, however, measurement errors from headphone and microphone placements are unavoidable. Moreover, measurement errors and individual characteristics are often mixed together, especially at high frequencies where both the measurement errors and the individual characteristics are obvious.

The object of this work is to evaluate the measurement error and individual characteristic in measured HpTFs by using a type of circumaural headphone (Sennheiser HD250 II) which has been proved to have a desired reproducibility [3]. In this work, HpTFs from six human subjects and a dummy head (KEMAR) were measured with headphone and microphone replacements. Deviations among various measurement sets were analyzed with equivalent rectangular bandwidth smoothing.

Measurements

A blocked-ear-canal technique is adopted in this study due to its high reproducibility [2]. The error sources in HpTF measurement include two aspects: headphone placement and miniature microphone placement. To evaluate the two kinds of measurement errors as well as individual characteristics of HpTF separately, we investigated three kinds of measurement conditions as shown in Table 1. In Set A, measurement difference is attributed to headphone placement, since the built-in microphone of B&K4192 is fixed at end of Zwislocki occluded-ear simulator. While, in Set B where the miniature microphone DPA4060 was removed after 10 repetitions (Set B1) and then repositioned for another 10 repetitions (Set B2), both headphone placement and microphone placement influence the measurement results. In Set C, the measurement difference includes the inter-individual HpTF difference caused by individual external ear dimensions, as well as the intra-individual difference (i.e. measurement error) introduced by headphone and microphone placements. A 8191-point maximal length sequence was used as measurement signal with 8 repetitions to improve the signal to noise ratio to 9 dB. The sample frequency is 44.1 kHz. After measurements, the original 8191-point measurements were truncated to 512-point by a time-domain rectangle window. Moreover, in order to remove the influence of the microphone, the measurements were equalized with the inverse function of the microphone response.

Table 1: Three sets in HpTF measurements

Sets	Parameters		
	Subject	Microphone condition	repetitions
A	KEMAR	B&K4192 Built-in	30
B	KEMAR	DPA 4060 Blocked ear canal entrance	10*2
C	Humans (3 male and 3 female)	DPA 4060 Blocked ear canal entrance	10

Results and analyses

To gain an insight into the perceptual significance caused by inter- and intra- individual differences, all measured HpTFs were smoothed with an equivalent rectangular bandwidth filter which accounts for the frequency resolution of the inner ear. The equivalent rectangular bandwidth is determined by

$$ERB\,Width = 24.7(4.37f + 1) \quad \text{[Hz]} \qquad (1)$$

where f is the center frequency in kHz. In this paper, only results of the left ear are presented, and the same methods can be applied to the right ear.

I. Standard Deviation

Figure 1 shows the standard deviations for each set after equivalent rectangular bandwidth smoothing, in which the curve of Set A represents the variation caused by headphone placement with built-in microphone, each curve of Sets B1 and B2 represents the variation caused by headphone placement in using block-ear-canal technique, the curve of Subject 6 reflects the intra-individual difference by comparing the 10 repetitions of a representative subject No. 6. Assume the intra-individual difference across the repetitions for a certain subject can be regarded as a random error, we can use the average of the 10 repetitions of a certain subject as the authentic HpTF of that subject. The curve of inter-subject in Fig. 1 demonstrates the variation of the authentic HpTFs among 6 subjects. According to Fig. 1, some discussions are followed:

(1) A general trend is that standard deviation is moderate below 0.8 kHz due to the different low-frequency leakage caused by different headphone placement. In mid-frequency range up to approximate 5-6 kHz, however, standard deviation decreases to below 1 dB for all sets. Note that, the maximum of standard deviation occurs at the frequencies of 8-10 kHz where the first notch is located. This notch in HpTF is strikingly similar to that in head-related transfer function which is well known as an important localization cue.

(2) According to curves of Sets A, B1 and B2, variability introduced by headphone placement is relatively small with the maximal standard deviation of 2.1 dB. Therefore, HpTFs with high reproducibility can be obtained by using this type of circumaural headphone.

(3) Because the difference between Sets B1 and B2 are merely due to different positioning of the miniature microphone, then the high similarity between the two curves implies that the measurement error introduced by placing the miniature microphone to different subjects by an experienced operator is negligible.

(4) In the overall audio frequency range, standard deviation representing the inter-individual difference is far larger than that representing the intra-individual difference of Subject 6, especially at high frequencies. This is also the case for the other 5 subjects. Therefore, we can reach a conclusion that the reliable individual characteristics in HpTFs can be extracted from measured HpTFs which contain measurement errors as well.

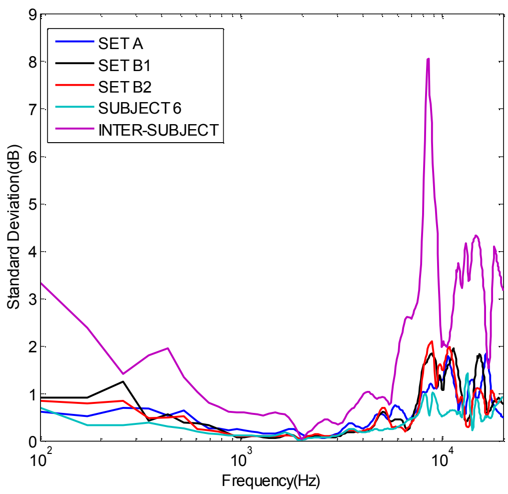

Figure 1: Standard deviations for Sets A-C with equivalent rectangular bandwidth smoothing.

II. Similarity in Spectral Profile

In order to further investigate the inter-individual difference and intra-individual difference, correlation coefficient among the magnitudes of HpTFs were calculated. As to intra-individual difference, almost all the correlation coefficients for each subject's 10 repetitions are lager than 0.90 with an average larger than 0.93. This means that the 10 repeatedly measured HpTFs for a subject are highly consistent in spectral profile. In contrast, as to the inter-individual difference, the correlation coefficients for 6 subjects' authentic HpTFs are all no more than 0.81 (even have negative values) with an average of 0.49, see Table 2. This indicates that each subject has his/her own HpTF with specified spectral profile due to specific pinna dimension. In synthesizing binaural signals for headphone reproduction, the spectral profile of HpTF partly determines the spectral profile at eardrum. So, the low similarity (i.e. large difference) among 6 subjects' HpTFs due to inter-individual difference is likely to cause audible difference.

Table 2: Correlation coefficient (CC) between HpTFs of the 6 subjects

CC	No.1	No.2	No.3	No.4	No.5	No.6
No.1	1.00	0.81	0.28	0.61	0.81	0.29
No.2	0.81	1.00	0.32	0.40	0.59	0.26
No.3	0.28	0.32	1.00	-0.07	0.00	-0.28
No.4	0.61	0.40	-0.07	1.00	0.69	0.58
No.5	0.81	0.59	0.00	0.69	1.00	0.55
No.6	0.29	0.26	-0.28	0.58	0.55	1.00

III. Statistical Significance

One-way multivariate analysis of variance was also applied to the HpTFs in Set C. Results show that there is a significant difference (at significance level of 0.05) among the 6 groups of HpTFs with each group for a certain subject.

Conclusions

This work investigated the intra- and inter-differences in HpTF measurement. Results show that reliable individual HpTF can be obtained by the circumaural headphone with blocked-ear-canal measurement, because the inter-individual difference (i.e. individual characteristic) is dominant in quantity, spectral profile, and statistics.

Acknowledgement

The authors acknowledge the support of Nature Science Fund of Guang Dong province Grant No. 07300617.

Literature

[1] Xie, B. S.: Head related transfer function and virtual auditory display. National Defense Industry Press, Beijing, 2008

[2] Wightman, F., Kister, D.: Measurement and validation of human HRTFs for use in hearing research. Acta Acoustica United with Acoustica 91(2005), 429-439

[3] Rao, D., Xie, B. S.: Repeatability of headphone-to-ear-canal transfer function measurements (In Chinese). Acoustical Technology 25 (2006), 441-442

[4] MØller, H.: Transfer characteristics of headphones measured on human ears. J. Audio Eng. Soc. 43(4) (1995), 203-217