On the effect of individual headphone compensation in binaural synthesis

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Introduction

Transducers involved in the binaural recording and reproduction signal chain introduce unwanted spectral coloration, which can become audible as soon as a binaural simulation is directly compared to the corresponding real sound field. Spectral differences are mostly due to loudspeakers and microphones used for the measurement, and to the characteristics of headphones used for auralization. The influence of the headphone transfer function (HPTF) can potentially be compensated using inverse filtering. According to results of a previous study [1] comparing several inversion approaches for HPTFs, high-pass-regularized least-mean-square (LMS) inversion [2] proved to be a perceptively well-suited algorithm. However, audible spectral differences remained, originating, at least partly, from using non-individual HPTFs for inversion in [1]. Therefore, this study examines the benefit of using generic and individual HPTFs while still applying the described LMS inversion algorithm.

Measurement method

In binaural technique, it is generally assumed that the complete spatial information is included in the sound pressure at the entrance of the blocked ear canal [3]. The eardrum signal can perfectly be reproduced from the sound pressure at the blocked ear canal, if headphones exhibiting an acoustic impedance close to that of free air are used (free field equivalent coupling, FEC [4]). Therefore, when used for binaural recordings, dummy heads are usually equipped with microphones at the blocked ear canals.

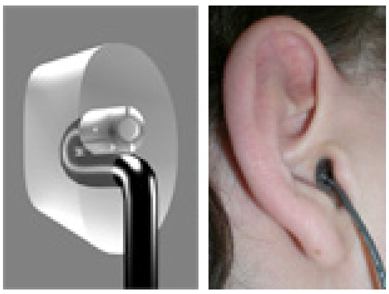

Figure 1: Silicone earplug. CAD model (left) and inserted in ear (right)

Thus, a method for measuring individual HPTFs at the blocked ear canal appears desirable. Consequently, silicone earplugs with flush-cast miniature electret condenser microphones (Knowles FG 23329) were custom-built in three sizes using anthropometrical data supplied by the manufacturer PHONAK (Figure 1). For testing the novel earplugs, transfer functions were measured on an artificial ear equipped with an ear canal, while reinserting the silicone earplugs after each individual measurement.

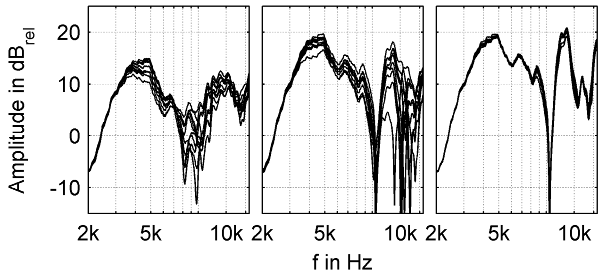

Figure 2: Ten transfer functions of an artificial ear measured with Knowles FG 23329 and EAR II foam plug (left), UVEX foam plug (middle), and novel silicone earplug (right), plugs were reinserted between each measurement

Deviations due to replacing the earplugs were negligible below 8 kHz; above, they reach a maximum deviation of ± 2 dB. When comparing these results to those obtained with commonly applied HPTF measurement techniques using foam earplugs (and mostly larger microphones), the new measurement method was shown to provide an increased reliability (cf. Figure 2) while being easier to conduct.

Measuring individual HPTFs

HPTFs of two female and 23 male subjects were measured using electrostatic STAX 2050 II headphones approximately meeting the FEC requirement [4]. HPTFs were measured ten times per subject, while headphones were repositioned between each measurement. For the vast majority of subjects, HPTFs could be reproduced sufficiently well. However, intraindividual deviations of typically less than ±2 dB below and ±5 dB above approximately 10 kHz will still limit future compensation accuracy.

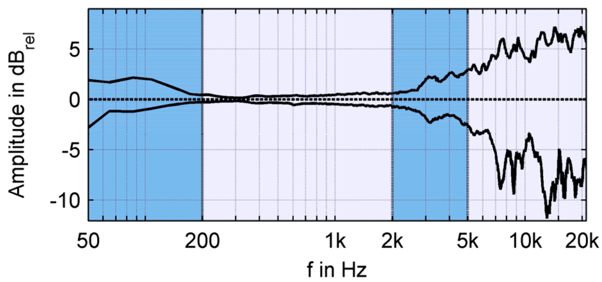

Figure 3: *12.5% - 87% percentile ranges of individual HPTFs (left ear)*

Differences in HPTFs across all subjects are depicted in Figure 3, showing the 12.5 % - 87.5 % percentile ranges of all 250 measurements. Four characteristic frequency ranges can be identified. Below 200 Hz, differences of ±3 dB are observable which can primarily be assigned to leakage effects. Up to 2 kHz, differences are smaller than 1 dB. Above 2 kHz and up to 5 kHz, deviations quickly increase to ±3 dB. Above 5 kHz, the region of narrow pinna notches begins.

Hence, deviations become asymmetrical and grow up to +7 and -11 dB, respectively.

Auditory modeling of inversion effects

The effect of using three different sources of data for generating the inverse headphone filter (non-individual, generic, and individual HPTFs) was assessed using an auditory filter bank. 2048-tap FIR-filters were designed using high-pass-regularized least-mean-square (LMS) inversion [2]. Non-individual headphone compensation is achieved by filtering the headphones with the inverse obtained from the HPTF of an arbitrary subject. To be comparable with [1], for the creation of the non-individual compensation filters HPTFs measured on the head and torso simulator FABIAN were used. For a generic compensation, the inverse of the average HPTF across all 25 subjects was used, whereas for individual compensation, the inverse of the subject's own average HPTF was applied. The target function employed for the creation of the inverse filters was a minimum phase band pass with -6 dB cut-off frequencies at 50 Hz and 21 kHz. An auditory filter bank of 40 equivalent rectangular bandwidth (ERB) filters [5] was used to model perceptual deviations between compensated HPTFs and the target function. For each filter band, differences were calculated between the target function and the individual compensation result after applying the appropriate inverse filter.

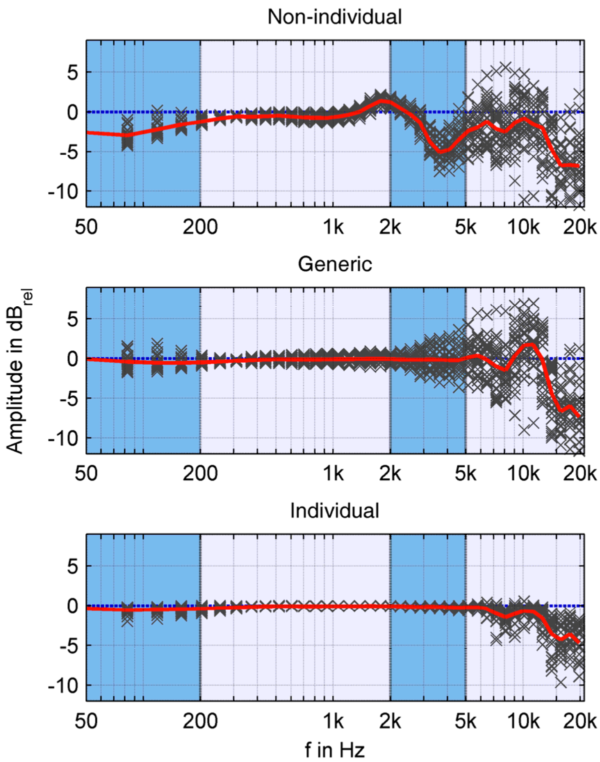

Figure 4: *Deviations of compensated HPTFs from target function for each band of an auditory filter bank for the three different inversion approaches. Grey: Mean deviation of single subjects. Red: Mean deviation across all subjects.*

Results and Discussion

For all three compensation approaches, deviations from the target functions are depicted in Figure 4. Non-individual compensation exhibits some leakage-caused damping below 200 Hz, considerable boosts and notches occur between 1 kHz and 5 kHz, whereas increasingly chaotic deviations can be found above 5 kHz. The generic compensation performs better; deviations are symmetrical around the target function up to 5 kHz causing less absolute error. Variance among the subjects remains unaltered. Besides, in comparison to the non-individual approach, the generic compensation reduces the maximum possible error: If HPTF magnitudes across subjects are – at each frequency bin – assumed to be symmetrically distributed, a generic filter based on the average HPTF will always halve the compensation error that would occur between a worst-case pair of individuals when using the non-individual approach. However, high frequency boosting emerges above 5 kHz; ringing artifacts might still be audible. High frequency boosting vanishes almost completely if individual compensation is applied. Potentially audible deviations below 200 Hz are most likely due to the limited frequency resolution of the FIR-filter. Between 200 Hz and 5 kHz, deviations stay within ±1 dB. For all methods, compensation results exhibit negative deviations above 6 kHz, due to the high-pass regularization used in the LMS inversion, where the compensation of narrow notches, which are assumed to be barely audible, is avoided. Auditory deviations from the target function are summarized in Table 1.

Table 1: Auditory deviation between compensated HPTFs and target-function (left ear, max/min in dB)

	50 Hz - 200 Hz	200 Hz - 2 kHz	2 kHz - 5 kHz	5 kHz - 21 kHz
Non-individual	+0.2 / -4.2	**+2.2** / -1.7	**+1.9** / -7.5	**+5.6** / -15
Generic	**+1.9** / -1.8	+0.9 / -1.1	**+3.6** / -3.6	**+7** / -13.7
Individual	0.3 / -2	0 / -1	0 / -0.6	+0.6 / -9.6

Conclusion

The effect of three different approaches towards headphone compensation in binaural synthesis was examined. Regarding spectral coloration, generic and individual compensation promise noticeable improvements when compared to the non-individual approach. Only an individual compensation promises complete elimination of the disturbing high frequency ringing, whereas perceptively less relevant notches remain uncorrected. Currently, a listening test aiming at a perceptual evaluation of the methods described is prepared.

Acknowledgements

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