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ABSTRACT OF DOCTORAL DISSERTATION

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Name of the dissertation
HRTF Analysis: Objective and Subjective Evaluation of Measured Head-Related Transfer Functions

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☒ Monograph		☐ Article dissertation (summary + original articles)	

Department	Electrical and Communications Engineering
Laboratory	Laboratory of Acoustics and Audio Signal Processing
Field of research	Acoustics and Audio Signal Processing
Opponent(s)	Prof. Dorte Hammershøi
Supervisor	Prof. Matti Karjalainen

Abstract

This work discusses *measured head-related transfer functions* (*HRTFs*) that incorporate all the basic auditory localization cues received by the auditory system, e.g., binaural interaural time and level differences (ITDs, ILDs), and monaural spectral filtering caused by the human body. The three-part thesis covers in great detail HRTF *repeatability*, *variability* and *idiosyncrasy*.

The first part of the thesis, i.e., *visual evaluation*, shows effects on HRTFs caused by variations in microphone placement, ear canal and *cavum conchae* occlusion, head posture and movements. Due to complex pressure distributions in the human concha, especially the transverse modes above ca. 10 kHz, and the strong head shadowing effect, the fundamental measurement uncertainty (repeatability) becomes poor at high frequencies and in contralateral directions. In ipsilateral directions, the reflections from the anatomy are more prominent than the diffraction phenomena, and the between-subject variability (idiosyncrasy) is maximal above ca. 6 kHz due to highly individual concha structure. The degree of idiosyncrasy is further affected by HRTF measurement distance, head/body posture and the person's outward appearance, e.g., hair/style, headpieces and clothes. Their effects follow complex but nevertheless generic principles enabling these (external) attributes to be parametrically modeled.

The second part consists of *computational assessment* of HRTFs*,* quantitative measures of HRTF measurement quality, and HRTF variability/idiosyncrasy. Various methods are presented to track down measurement errors and abnormal behavior due to, e.g., acquisition errors, non-optimal microphone placement, *cavum conchae/meatus* occlusion, and abnormal head postures. Functional modeling methods, such as principal component analysis, are tailored for finding deviant data and for examining quality of HRTF databases and measurement systems. Moreover, an *ad hoc* approach is presented to estimate HRTF idiosyncrasy that objectively measures inter-individual variation by applying basic localization cues to yield a deeper insight into HRTF characteristics.

In the last part, nine various behavioral experiments are performed in order to *perceptually evaluate* measured HRTFs and determine various issues related to the study of spatial hearing. Auralized HRTFs embody localization and distance cues only weakly compared to real life so that naïve subjects perceive differences poorly in monaural and interaural spectral cues originating from the various heads measured. This in turn leads to overly similar median plane localization performance. Even individual HRTFs are not generally superior for untrained listeners; different HRTF sets mostly cause only weakly dissimilar elevation perception. Untrained subjects listening to non-individual HRTFs indicate consistently ca. 20 % poorer localization acuity for right lateral hemifield targets when compared to left targets. These results are quite dissimilar to those from a single expert listener, except for perceiving differences in timbre: the most pronounced effect of all is obtained by using different types of headphones yielding dissimilar vertical localization. Multimodal experiments show no influence on the McGurk effect due to spatial segregation between virtual auditory and visual stimuli. The common ventriloquism effect associated with real sources is observed also in virtual listening but only in the median plane, suggesting that vision overcomes the weaker monaural but not the stronger binaural localization cues. Magnetoencephalography experiments applying individual HRTFs demonstrate further that binaural cues are processed earlier than monaural ones and indicate contralateral hemispheric dominance with respect to sound location. The earlier and more widely distributed responses in the right hemisphere imply that complex sounds including both monaural and spectral cues are processed in more detail in the right auditory cortex. The results suggest that once the listener has learned to perceive the virtual localization cues, the two lateral hemifields are localized equally well and the M1 and M2 cortical responses increase in magnitude but their latencies remain unchanged.

Keywords: 3-D sound, head-related transfer function, magnetoencephalography, spatial hearing, ventriloquism effect

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