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Reliability in Measuring Head Related Transfer Functions of Hearing Aids

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1 Introduction

Head related transfer functions (HRTFs) are a numerical representation of spatial acoustic cues. They are important in applications like modeling spatial hearing [1, 2]. Since HRTFs depend on the listener's head and ear, HRTFs are listener-specific [3]. Listener-specific HRTFs are especially important for applications like fitting hearing aids to children [4] or providing accurate sound localization performance via headphones [5].

The reliability of HRTF measurements was investigated by Møller *et al.* [6] and Wightman *et al.* [7]. Møller *et al.* showed good agreement between HRTFs measured under the same conditions at different days and Wightman *et al.* showed the variability in HRTFs caused by head movements and microphone placement. In both cases, HRTFs were obtained for a human test subject with a microphone placed in the ear canal. The reliability of HRTFs measured with hearing aids is less well explored.

Hence, in this study, HRTF measurement reliability with microphones placed in hearing aids was investigated. Further, we used a 3D printed head model as a supplement to the human test subject, exploiting the benefit of excluding head movements usually present when measuring human listeners. A listener-specific head model might replace time-consuming measurements on a human test subject, and it is therefore interesting to know the reliability of such measurements, and to compare it with the reliability of HRTF measurements on human test subjects

2 Material and methods

2.1 Generation of 3D printed head

A listener-specific 3D head and ear model was generated using the framework in [8]. The 3D model was based on a number of 3D surface scans of the human listener NH167 from

the ARI database (<http://sofaconventions.org>). The scans were obtained using a Canfield Scientific Vectra M3 surface scanner and were captured from different angles surrounding the head. The surface scans were then aligned and stitched together using a higher-order mathematical model.

The complete 3D head and ear model, which consists of vertices and triangles, was converted to non-uniform rational B-splines (NURBS) [9]. The head model was further processed to add an artificial thickness, with an overall minimal thickness of 5 millimeters, for for printing purposes.

In order to mount onto a torso simulator (Type 4128, Brüel & Kjær) after the printing, a flange was added to the model at the bottom of the head. Further, boxes around the ears were created to facilitate printing of the head and ears separately using different materials.

The ears were printed on a polyjet Objet500 Connex 3D printer using two materials and a layer thickness of 0.03 mm. The core was printed in a hard, acrylic material (Verowhite - FullCure830) and the outer part was printed in a soft material (Tango-Plus - FullCure930). The hard part of the head was printed on an SLS printer EOS P395 in hard acrylic (PA2200) using 0.12 mm layers. The soft material for the ears was chosen to facilitate hearing aid placement, whereas the impedance properties of the materials were of less concern, since it has been shown that the ear entrance sound pressure are relatively insensitive to surface or skin impedance [10].

2.2 Acoustical measurements

HRTFs were measured in a semi-anechoic chamber. Twenty-two loudspeakers were mounted on an arc at fixed elevations from -30° to 80° , (for more details on equipment, see [11]). The printed head was fixed on a torso simulator (Type 4128, Brüel & Kjær) and placed in a chair in the center of the arc, such that the HRTFs were measured for an azimuth angle of 0° . The printed head or human subject was wearing hearing-aid shells with microphones on both ears. Two types of hearing-aid shells were used: behind-the-ear (BTE) and completely-in-canal (CIC), with Knowles FG 8000 microphones. The microphones were connected via amplifiers to the digital audio interface. A 1728.8-ms exponential frequency sweep beginning at 50 Hz and ending at 20 kHz was used to measure each HRTF. Note that in the analysis, we were interested in the frequency range used by hearing aids, i.e., up to 10 kHz only.

The HRTFs were affected by the loudspeaker, room, microphone, D/A converter and amplifier used for the measurements. These effects can be described by the equipment transfer functions (ETFs). ETFs were captured with a reference measurement in which the microphones were placed in the center of the arc and the room impulse response was measured for all loudspeakers. Room reflections were initially removed from both the HRTFs and the ETFs by windowing in the time domain.

The remaining loudspeaker and microphone responses were compensated in the frequency domain. For a given microphone k , a compensated HRTF $C_k(\theta, \phi)$ at elevation θ , and azimuth ϕ , was calculated as

$$C_k(\theta, \phi) = \frac{H_k(\theta, \phi)}{E_F(\theta)}, \quad (1)$$

where $H_k(\theta)$ is the windowed raw HRTF for microphone k and $E_F(\theta)$ is the windowed ETF for the front microphone in the BTE hearing aid.

In this way the HRTFs are compensated for room and loudspeaker responses, however they are not compensated for the individual microphone response. The small phase differences that exist between the BTE microphones are highly important for hearing-aid directionality [12]. The best way to retain the phase difference during the post processing was to use the ETF for one microphone in a set of BTE microphones, instead of compensating each microphone using their respective EFT. It is hereby assumed that the two matched microphones in a BTE hearing aid have equivalent microphone responses.

2.3 Conditions

The measurements were repeated under various conditions. In the condition *HAD*, hearing aids were detached from the head and re-attached before the next measurement. In the conditions *Tripod1* and *Tripod2_s*, the tripod carrying the torso, head, and the hearing aids was removed from the arc center and placed back. Furthermore, hearing aids were detached from the head and re-attached. *Tripod1* and *Tripod2_s* were performed with the same conditions, however on two different days. All conditions except *Tripod2_s* were measured five times. The *Tripod2_s* has a subscript *s* to indicate a single measurement. In the condition *Control*, the measurements were repeated without any intervention.

As a further control condition, single measurements on the actual human listener were performed on two different days yielding *Human1_s* and *Human2_s*, respectively. Note that the human listener was the model for the 3D printed head, thus, the listener and the printed head shared the same anatomical details.

All conditions were measured for both CIC and BTE hearing aids with the exception of the condition *HAD*, which was not measured for the CIC hearing aid because of difficulties with repositioning the hearing aid. The ear canal of the printed head was not as flexible as an ear canal on a human, and insertion and removal of the CIC was difficult to control.

Furthermore, for the CIC microphones in condition *Tripod1*, only the head and torso and not the hearing aid were repositioned.

3 Results and discussion

3.1 Within-session repetitions

Figure 1 shows spectral amplitudes of five HRTF measurements for each of the three conditions: *Control*, *HAD*, and *Tripod1*. The HRTFs are shown for the left-frontal (LF) microphone of the BTE hearing aid and for the exemplary direction of elevation angle of 15° (other elevation angles showed similar results). In the figure, the magnitudes are offset by 5 dB between conditions for better readability. The top panel shows the absolute amplitudes

and the bottom panel shows the amplitudes relative to the average. It appears that from Control over HAD to Tripod1, the measurement repetition introduced more variation to the measurements. This is in agreement with the measurement conditions, because from Control over HAD to Tripod1, more and more parts have been re-positioned between the measurements. Nevertheless, the variability is below 1 dB in most cases.

Figure 2 which shows HRTF magnitude spectra based on a single measurement for conditions Control, HAD, and Tripod1 measurements. The HRTFs seem to be similar in the three conditions for all elevation angles, supporting that the findings for the single elevation shown in detail in Figure 1 are general.

In order to quantitatively analyze the variability for all tested directions and hearing aids, spectral standard deviations (SDs) were calculated across the five measurements for each frequency and condition. The average across frequency of these SDs calculated between 0.2 and 10 kHz is shown in Table I.

A very small variability is observed in the condition Control, with a standard deviation of 0.01 dB. The obtained HRTFs were practically identical, leading to deviation close to zero. The HRTFs measured in the condition HAD showed an average SD of 0.46 dB, which indicates less reliability than that found in the condition Control, however still providing reasonable reliability. The HRTFs for condition HAD were still quite similar for the five repetitions, however frequency dependent variability was observed, with larger deviations at higher frequencies. The condition Tripod1 was similar, with respect to variation between measurements, to the condition HAD, with an average SD of 0.34 dB. Also in the condition Tripod1, the deviations were frequency dependent, with larger variability at higher frequencies. In addition, larger deviations were also observed at lower frequencies.

The similar reliability in the conditions HAD and Tripod1 indicates that the exact position of the printed head was less important than the position of the hearing aids. It therefore appears that the variability in the Tripod1 condition was caused mainly by small errors in re-positioning the hearing aids. The larger variability between measurements at higher frequencies seems reasonable, since both conditions, HAD and Tripod1 were subject to small changes in hearing-aid position. The condition Tripod1 also revealed variability at lower frequencies (below 1 kHz), which indicates that the re-positioning of the head and torso involved larger position changes.

Table I shows SDs for four microphones of the BTE hearing aids (2 microphones per ear) and for both microphones of the CIC hearing aids (1 microphone per ear). Note that the condition HAD was not measured for the CIC hearing aid because of difficulties with repositioning the hearing aid. Table I shows that the SDs were similar across microphones for each condition indicating that the variability does not depend on the type of the hearing aid. Note that the CIC hearing aid has a SD comparable to the BTE for the Tripod case even though the hearing aid was not repositioned. The CIC measurements might be more sensitive towards movements of the printed head, because pinna effects arise due to the hearing aid position in the ear canal.

3.2 Across-session repetition

Figure 3 compares two HRTFs across two measurement sessions for both the printed head and the human subject. The measurements used are the first Tripod1 measurement (referred to as Tripod1₁ in the following), Tripod2_s, Human1_s and Human2_s. The average SDs were 0.88 and 1.5 dB for the Tripod and Human conditions, respectively. The variation between measurements from different sessions are clearly larger than that from the same session. Between the sessions, changes in the measurement setup such as re-positioning of acoustic damping material on floor and equipment, re-wiring of the hearing aids, as well as small temperature changes might have been involved. The variation in our HRTFs measured at different days is comparable to the variations shown in [6] measured under similar conditions.

A larger SD was obtained for the Human1_s and Human2_s measurements, as compared to the SD obtained for the Tripod1₁ and Tripod2_s. This corresponds to a larger variability when HRTFs are measured for the actual human listener than when measured using the printed head. The higher variability is most likely the result of small but unavoidable movements of the head and body, for instance due to breathing. These issues are not involved in measurements performed on the printed head, being reflected in smaller SD and thus better reliability of the measurements using the printed head.

4 Conclusions

Repeating HRTF measurements yields a variability in the results. Simple repetition without any repositioning of the microphones were very reliable, showing standard deviations about 0.01 dB. Repositioning of the hearing aids had a larger effect on the reliability, with standard deviations up to 0.6 dB. Additional repositioning of the printed head did not substantially increase the variability. All of the within-session results are valid for a printed head model and equivalent accuracies can not be assumed for a human subject. HRTFs measured in different sessions, however, showed a larger variability attributed to less controlled measurement conditions. Our results indicate that the repeatability of HRTF measurements with human listeners has its limitations, but that the repeatability is high for HRTFs measured using a head simulator instead.

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Figure 1. HRTF magnitude spectra for elevation of 15° and conditions Control, HAD, and Tripod1, each repeated five times. Top panel: Absolute magnitudes with an offset of 5 dB between conditions. Bottom panel: Deviation from the average with an offset of 1 dB between conditions for visualization purposes.

Figure 2.
 (Color online) HRTF magnitude spectra in the median plane (as function of elevation angle).
 Color encodes the relative magnitude in dB. F, T, R indicate the front, top, and rear
 directions, respectively.

Figure 3. HRTF magnitude spectra for elevation 15° and measurements Tripod1₁ and Tripod2_s, and Human1_s and Human2_s. Absolute magnitudes with an offset of 10 dB between conditions for visualization purposes.

Table I

Standard deviations (in dB) calculated for the five repetitions for each elevation angle and averaged over the frequency range from 0.2 to 10 kHz. BTE microphones: left front (LF), left rear (LR), right front (RF) and right rear (RR). CIC microphones: left (L) and right (R).

	BTE				CIC	
	LF	LR	RF	RR	L	R
Control	0.01	0.01	0.01	0.01	0.03	0.03
HAD	0.46	0.60	0.36	0.53	-	-
Tripod1	0.34	0.39	0.41	0.72	0.56	0.58