Part IIIa: Effect of Microphone Position Changes on Blocked *Cavum Conchae* Head-Related Transfer Functions

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Abstract

The first part of the current triplet work relating to the qualitative matters of *head-related transfer functions (HRTFs)* investigates the effect of *varying the microphone position* at the silicone *blocked meatus*. The applied measurement system and method is shown to be highly accurate, and two subjects are employed for the repetitive measurements. When the capsule is moved 2-3 mm from the *tragic apex* to the *cavum conchae*, distinguishable smooth transitions depending on the frequency, elevation, azimuth and ear are noted. The findings suggest that even relative small positional changes in the capsule position alter notably the HRTF characteristics, i.e., the *cavum conchae eigenfrequencies*, in the order of ~±5 dB (<10 kHz) to ~±10..15 dB (≥10 kHz).

1. Background

Human spatial hearing is based on the binaural and monaural spectral cues, which are embodied in head-related transfer functions (HRTFs). A HRTF is defined as the sound pressure (SP) measured (or modeled) at a point in the ear canal (*meatus*), divided by the SP in the middle of the head the subject absent. HRTFs are considered as linear and time invariant (LTI) systems [1, 2].

All the studies of the current triple paper [3, 4, 5] apply HRTF data obtained by the author's old measurement system ($1^{st}/2^{nd}$ generation) that is discussed in detail in [6, 7]. The system has been already modified to its 4^{th} generation, into a much more sophisticated multimodal system reviewed in [8]. However, many of the methods and results presented in the current three studies are of fundamental nature and will valid to all HRTF measurements, independent of the actual measurement system used.

2. Introduction

Because this study goes into the very delicate HRTF quality characteristics, i.e., the petite microphone position changes around the human *cavum conchae*, the overall underlying disruptive matters need to be addressed first.

2.1. Quality of HRTF measurements

Like all (electro-) acoustical investigations, HRTF measurements are susceptible to all shorts of electrical, acoustical and physical faults affecting the quality of the results; see, e.g., [1-9].

2.1.1. Disrupting factors

There are two physical inconveniences in HRTFs that cannot be avoided:

a) the head shadow effectively lowers the SNR of the contralateral ear (but it is also the most important localization aid), and

b) the minor body/head asymmetry making the analysis more difficult (but the effect is virtually insignificant).

However, one should consider many other disrupting factors possibly present during HRTF measurements. They could be caused by any combination of the following:

c) errors / faults created by the measurement system and/or surroundings,

d) human errors / faults by the experimenter,

e) inaccuracies in positioning the test subject, i.e., the head,

f) subject's (head) movements,

g) subject's incorrect head posture (e.g., the (slow) changing of the head position during measurements),

h) inaccuracies in blocking the ear canal (+effects of various ear plug materials) and

i) *inaccuracies in positioning the microphones at the two ears.*

Moreover, in repetition measurements there are additional difficulties that are strengthened if more time has passed between the recording sessions:

j) instability (time variance) of the measurement system, changing hardware etc.,

k) artifacts due to the use of different microphones,

l) changes in outward appearance of the test person (garments, hairstyle, spectacles etc.) and

m) alteration in subject's (head) anatomy (pinnae / head growth with young people, surgery after trauma etc.).

2.1.2. *Verification of quality*

The list in the previous section is multifold and demonstrates well the *complexity in doing accurate* (real head) *HRTF measurements*. Considering cases c-e), they can be well estimated by verifying the repeatability of dummy head measurements, using its built-in microphones. Further information on h), i) and k) can be obtained by using external miniature microphones. The factors c), j) and k) are revealed by system measurements, and j) will be revealed by repeating the system recordings after a long time interval.

Because of space limitations, this paper describes next only briefly the data verification; full analysis in carried out in [8]. Repetition measurements (after the disassembly and a 3-week pause) with a Cortex MK II dummy head, using both built-in B&K4190 microphones and Sennheiser KE4-211-2 capsules at the open *meatus*, show an absolutely negligible variance of less than ±0.5 dB for the whole frequency range of 0.2-24 kHz. Furthermore, [5] describes *only a typical ±1..2 dB variation* in the whole frequency range when repeating real head measurements without repositioning the capsules, which proves that a high accuracy is also obtained (by the author) with real head HRTFs. This proves the following points valid:

c) the electro-acoustical system is of the highest quality,

d) the experimenter (author) has been very careful and,

e) the procedure of positioning the test subject is very accurate,

i) the experimenter has *re-positioned the capsules* at the *open meatus* well to the same position.

The applied system compensation method cancels well out the effects j) and k). This is even apparent considering the high time-stability of the system; the system responses measured over 2.5 years show less than ±2 dB (200–18000 Hz) elevation independent variation, even using different microphones (!). With significant system modifications during the 6 six years the frequency responses still vary less then ±5 dB (!).

2.2. Means of analysis

Current investigations consider small variations between different treatments. Therefore, the succeeding system compensated frequency responses indicate the *point-to-point* dB-magnitude *difference* of the *particular measurement* compared to the chosen *reference* response. Furthermore, in order not to display too small differences that have no relation to the auditory perception, all data is *smoothed 0.1 octave*. The plots are adjusted to the same average level calculated at frequencies below 1 kHz, which removes the fixed gain offsets between the conditions. A large set of sound incidents is used to show the results covering the complete three-dimensional space.

3. Effect of microphone position changes at blocked *cavum conchae*

The following investigation concentrates on the specific effects of varying the position of a *miniature electret microphone* (Sennheiser KE4-211-2, ø=4.75 mm) at the entrance *real ear canals*, blocked with moldable *silicone* polymer.

3.1. Data collection

The data collection was done with the highest demand for care; the author performed the subject positioning most accurately [6, 7]. Two able test persons (*R1* and *R2*) sat still during the measurements covering 252 sound incidents (δ=±30°,±15°,0°,60°,90°, θ=0°:10°: 360°), see Fig. 1. The first measurement set was done in February 1997, when both the subjects were 28 years of age. The second set was collected in September 1999.

The data investigated here applies the left ear responses of subjects R1 and R2, see Fig. 2. The right ear photographs and measurement data are studied in the facing paper [4]. The third part [5] focuses on the influences of head movements and incorrect postures.

Fig. 1. Accuracy of the test subject positioning procedure, subject R2 taken as an example. A) 02/1997, θ=0°; b) 02/1997, θ=90°; c) 09/1997, θ=0°; d) 09/1999, θ=90°.

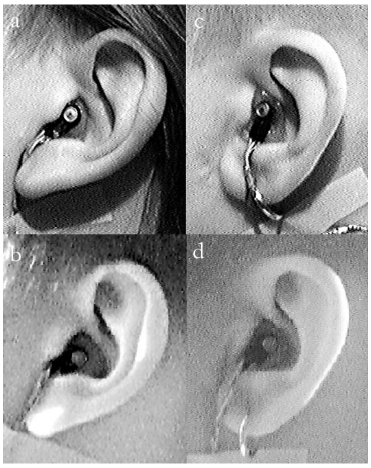

Fig. 2. Close-up photos of microphone + silicone positions. A) subject R, 02/1997; b) subject R1, 09/1999; c) subject R2, 02/1997; d) subject R1, 09/1999.

3.2. Other effects in HRTFs under test

Relating to Section 2.1.2, the effects of c-e) stated in Section 2.1.1 are insignificant in the current case. Furthermore, j) and k) have no affect as the data is system compensated, and h) is studied in [4]. Cases f) and g) were visually verified to be insignificant already during the measurements, this can also be deduced based on the general results in [5]. Fig. 1 confirms the constant head position and that l) and m) are non-existing; both subjects were full-grown, and had not experienced any physical change in their head/pinna anatomy after the first measurement occasion.

In all, the following analysis can be considered to be a valid investigation of case i), i.e., the effects of the varying microphone position.

3.3. Results

Fig 3. shows the dB-difference between corresponding left ear HRTF data from two measurements sessions performed on subjects *R1* and *R2*. Both the subjects indicate similar major trends in both their ear responses (as noted in [4] for the right ears), which further reinforces the following.

1) Subject *R1* shows three *resonance structure changes shifting smoothly in frequency depending on the elevation and the azimuth*. A minor change (+2..+5 dB) occurs in the *6-9 kHz band* and two major transforms (-10..-15 dB) in the *9-16 kHz and 16-20 kHz bands*. Unlike the other changes, the ca. 15 dB boost above 20 kHz is also present at high elevations (δ=60°, 90°).

2) Subject *R2* shows also three more or less similar resonance structure variations, approx. *at 6-9, 10-13 and 13-18 kHz bands*. They are somewhat less smooth and intense (~±8 dB) than with *R1*.

3) The close-ups photos in Fig. 2 indicate slightly different microphone positions. In the first measurement session (a, c) the capsules are close to the *tragic apex* (egde of *tragus*), where as in the second occasion the microphones are next to the midpoint of the *cavum conchae*. The variation in the capsule position is noted with the both subjects, but slightly more for the subject *R1*. The maximum change in the placement is approx. half the diameter of the capsule, i.e., 2-3 mm.

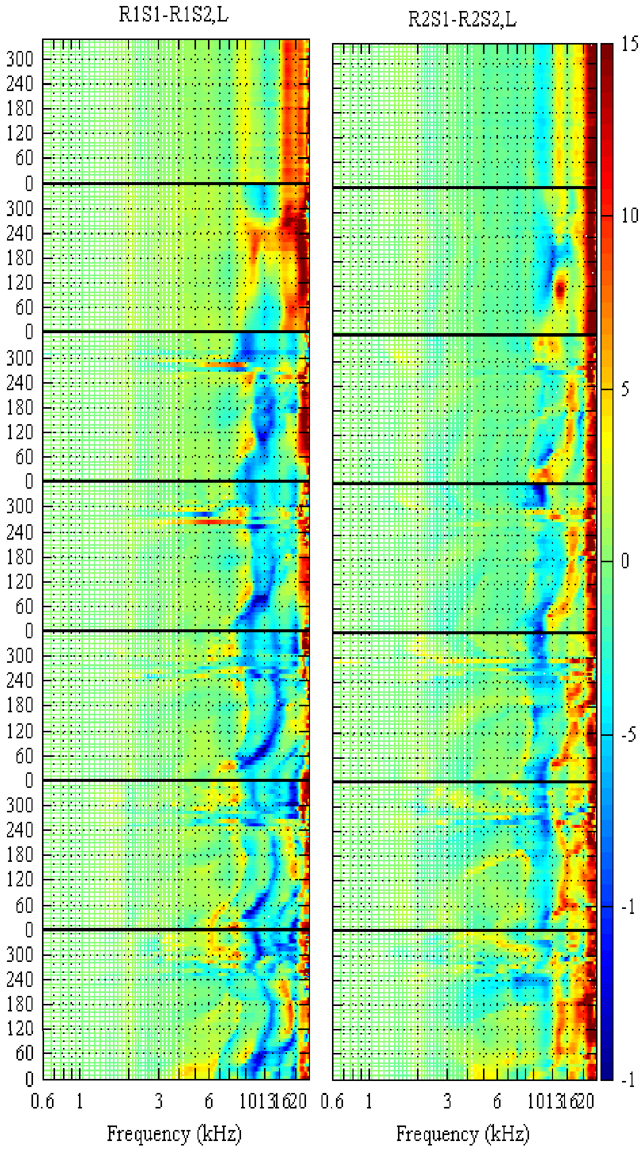

Fig. 3 Difference plots of the silicone repetitions. Left: subject R1 (left ear differences); right: subject R2 (left ear differences). The directions are shown in ascending order; the azimuths are shown in the order of (0°:10°:350°) per each elevation. The thick line splits the elevations (-30°, -15°, 0°, 15°, 30°, 60°, 90°) in ascending order from the bottom. The subjects' right ear curves are illustrated in [4, Fig. 3].

4. Discussion

The above findings give further empirical implication to the *natural resonances* in the *pinna* found by Shaw and Teranishi [10] and studied in detail further, e.g., by Shaw, (see for example [11]). The elevation-azimuth dependent frequency shifts noted in Fig. 3 are due to alterations in the *cavum conchae eigenfrequencies*.

The effects of the *meatus* and *pinnae* have been investigated in a number of occasions with probe microphone techniques with real subjects (see [12] for a modern study and review). However, the very different blocked auditory canal measurements have not yet been investigated so frequently. Besides the author, Algazi *et. al* [13] have studied this case for two real subjects and a KEMAR dummy head. They note that there are large individual differences and the measurements are very susceptible to positional and other errors. Their normalized residual error calculus, however, does not yield to a very clear general view of the dilemma. To sum up, they found (along with the author [7, 5, 8]) that there is notable variation between repetitive HRTF measurements above ca. 5 kHz, around ±5 dB or more.

The author's current presentation has originated from a more straightforward method, and the studies at hand [3-5] show lucidly in the whole three-dimensional space how complex it actually is to measure HRTFs of real heads.

What is also important is that the HRTF changes are not present at the top (δ=90°) elevation. This further reinforces the fact that the above direction is "blind" to minor changes in the microphone placement. However data from this direction shows whether the ear blockage has been successful between the repetitions, see [4]. In any case, the two factors – variation in ear blockage and capsule position – are obviously highly interrelated.

5. Conclusions

This first part of the triplet paper [3-5] discussed the underlying problems of HRTF measurements and concentrated on a specific one, i.e., the effect of varying the positions of miniature microphones at the entrance of the blocked *meatus*. The results from two real subjects show individual behavior, with a similar major trend, i.e., a smooth changing of the idiosyncratic resonance structures as a function of azimuth and elevation. This suggests that the *eigenfrequencies* in the *cavum conchae* [10, 11] are quite sensitive to the recording position. They undergo ear-specifically minor changes (~±5 dB) below ~10 kHz and much larger alterations (~±10..15 dB) above that frequency, when the capsule is moved a minor distance of ~±2..3 mm around the (blocked) *cavum conchae*. Further proof for the alterations of the *cavum conchae eigenfrequencies* is given in [4].

6. Acknowledgements

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