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Differences in dummy-head HRTFs caused by the acoustical environment near the head

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Filtering of the Head-Related Transfer Functions (HRTFs) is the first and most important part during the perception of directional information in spatial hearing. A computer-controlled dummy-head measurement system was installed in an anechoic room with 1 degree horizontal and 5 degrees vertical resolution. Differences in the measured HRTFs caused by changes of the acoustical environment near the head are calculated. Effects of “everyday objects” like caps, hair, glasses and clothing on the fine structure of the HRTFs are presented.

INTRODUCTION

Human localization performance and the quality of transmitted sound is one of the most investigated areas on the field of spatial hearing research. Spatial information in the sound waves is “decoded” by the auditory system and this leads to the perception of the sound field. Former investigations suggest the importance of the fine structure and accuracy of the applied HRTFs by sound-field simulation using headphone playback. On the other hand, localization in real life is not influenced very much by changes in the HRTFs if we put on a hat or let the hair cut. The aim of this study is to analyze how much the acoustical environment near the head affects the fine structure of the HRTFs.

1. THEORY

Localization means finding the location of a sound source. Fig. 1 shows the commonly used coordinate system related to the listener’s head. The sound source parameters are defined with r (distance), φ (azimuth) and δ (elevation) as usual [1]. This directional information is “encoded” in the spectral and temporal modifications of the propagating sound waves, and it is decoded through spectral and time-domain analysis of the auditory system.

It is well known that the outer ears play a significant role at the first step in the hearing system. The individual shape of the pinnae, head and torso influences the transmission as a linear, direction-dependent filtering. These sets of complex filters are the so-called Head-Related Transfer Functions (HRTFs) describing in each direction the transmission from the free-field to the eardrums [1–8].

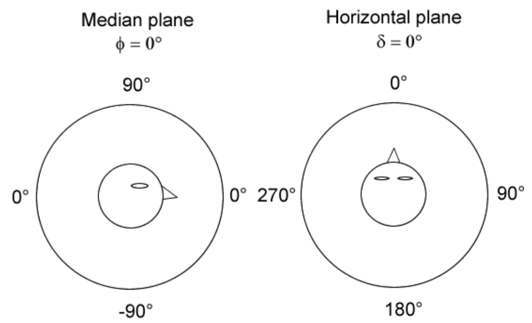


Figure 1. The Head-Related Coordinate System.
Sound sources are identified by elevation angle (δ) and azimuth (φ)

1.1. HRTF measurements and practical applications

The HRTFs can be measured on real human subjects or on dummy-heads [4–11]. The advantage of HRTFs recorded on human subjects is to have individual HRTFs for each subject and during playback this may result in a better localization performance. These measurements need human interaction and are made with impulse excitation with limited Signal-to-Noise ratio (SNR) and spatial resolution [10–12]. The dummy-head method may use broadband noise stimuli (mostly pseudo random noise signal) or sweep signals with increased SNR and precision. In this case we do not have individual HRTFs and averaging is also required. The use of dummy-head HRTFs in binaural reproduction results in decreased localization performance due to the "averaged" and just partly modeled human head, body and pinnae. Recordings made on dummy-heads do not have the same quality as recordings made on any other randomly selected or average human head [12–14]. To get a better localization performance without individual measurements some simple methods exist for individualising these HRTFs [11, 15–18].

The individual filtering of the HRTFs is present in our everyday life, but it has to be generated electronically and reproduced "exactly" during virtual audio synthesis through headphones to produce the same auditory event (perception) as by the recording [19–23]. This is mostly made by real-time convolution of the input signal and the time-domain version of HRTFs: the Head-Related Impulse Responses (HRIRs). Equalization of the applied headphone is necessary. Nevertheless, even with proper equalization and setting of individual parameters of the head or pinnae, typical headphone playback errors can occur, such as in-the-head localization, elevation shift or front-back reversals [22–30]. These errors are due to other dynamic parameters, such as changing of the HRTFs during head tracking, or to missing room reverberation [31]. In general, sound field synthesis (localization performance) via headphones is inferior to reproduction with loudspeaker playback or free-field listening.

1.2. Quality of HRTFs

The complex HRTFs contain information in the magnitude response and in the phase spectrum. In an accurate spatial simulation the phase information can probably not be neglected (describing low frequency torso effects). After all, the minimum-phase-filter assumption of the HRTFs allows the specification of their phase by its magnitude response alone, so HRIR specifications and time-delay information can be handled separately [32, 33].

For every headphone-based playback system it is necessary to integrate the HRTF filtering. It has been suggested that the “quality”, accuracy, and spatial resolution of these HRTFs determine the transmission (e.g. the need of individual HRTFs) and thus, the localization performance. The fact is subjects deliver better results in listening tests with individual HRTFs than with others [11–14]. Different sets of HRTFs can be regarded as “inaccurate”, and this suggests the importance of the fine structure of the applied HRTFs. It calls for a better HRTF recoding procedure (more detailed dummy-heads, increased spatial resolution, individual recordings) and for the most accurate HRTF synthesis during playback (headphone equalization, good SNR etc.).

To determine the variations in the fine structure of the HRTFs caused by the environment near the head, a precisely controlled dummy-head measurement system was installed in an anechoic room. The effect of “objects” we use everyday – cap, glasses, hair and clothing – was determined based by computing spectral differences in measured data.

1.3. Terms of use

Only the magnitude response of the HRTFs is used for further investigation at this point. The HRTF Difference (HRTFD) was introduced and found to be appropriate to evaluate differences between measured HRTFs from the same direction [25]. In this case, the HRTFD from a given direction can be calculated as:

$$HRTFD(\delta,\varphi) = \frac{HRTF(\delta,\varphi)_{C_1}}{HRTF(\delta,\varphi)_{C_2}}, \tag{1}$$

where C_1 identifies the reference and C_2 identifies a modified environmental condition. The C_1 reference corresponds to the HRTF of the bare torso and C_2 – to the HRTF of the dressed torso (e.g. wearing a cap).

The HRTFD gives us the difference in dB at all frequencies, thus, highlights the effect of the object we put on the torso. Dividing will eliminate individual properties (size, form etc.) of the applied torso.

We can plot the magnitude response of the HRTFD as the function of frequency for a fixed elevation and azimuth on Fig. 3–5. Other spatial-domain representation of HRTF data can be found in [38, 39].

HRTFDs are useful tools. By calculating them between HRTFs under unmodified conditions (C_1 = C_2) in repeated measurements we get the acoustical effect of the bare head and torso simulator, as presented in [25]. Next we are searching for significant and representative effects in the frequency to find how, where and how much objects near to the head influence the HRTFs.

2. THE MEASUREMENT SETUP

Details and some former results made with this system are described in [25, 32, 34–37]. The Brüel&Kjær Head and Torso Simulator Type 4128 is placed on a computer-controlled turntable in an anechoic room. The excitation is a modified pseudo-random noise signal with frequency-independent SNR [36]. The sampling frequency is 50 kHz, the resolution is 16 bits and the applied FFT has 4096 points. Existence and elimination of room reflections was investigated in this context and the system was found to be appropriate for long-term measurements [25, 36, 37]. The spatial resolution is 1 degree horizontally and 5 degree vertically. The transfer function of the 1,8 m distant loudspeaker and any other elements in the signal path (microphone, amplifiers etc.) are eliminated by the reference spectrum, i.e. by the normalization that defines an HRTF. Validity of the measured HRTFs is above 200 Hz. The measurement system has a repeatability of about 0,5 dB independent of frequency, elevation and azimuth using an unidirectional microphone. This means, all of the re-measured transfer function differences are within a 0,5 dB domain at all frequencies (Fig. 2). A transfer function difference is defined as the quotient of two re-measured transfer functions of the same system. Eq. 2 applies this on the Head-Related Transfer Functions. Using this system we can find physical effects corresponding to specific deviations in the fine structure of the HRTFs.

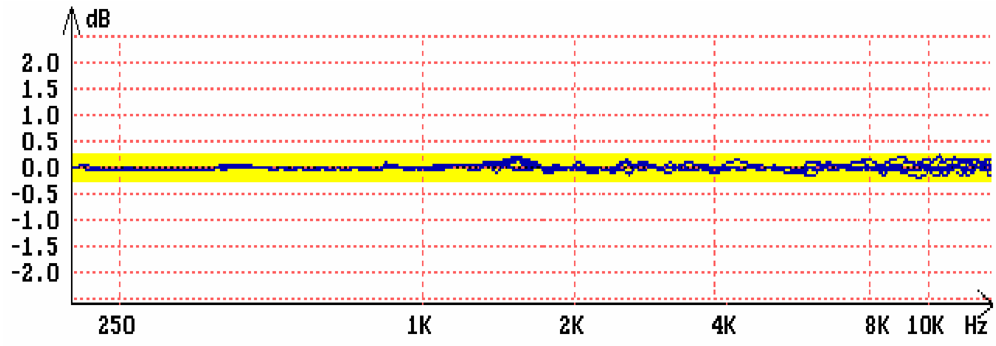


Figure 2. 20 re-measured transfer function differences with the measurement system using the BK 4166 unidirectional microphone placed on the turntable. All are within a 0,5 dB domain (highlighted) that corresponds to a repeatability of 0,5 dB in the entire frequency region

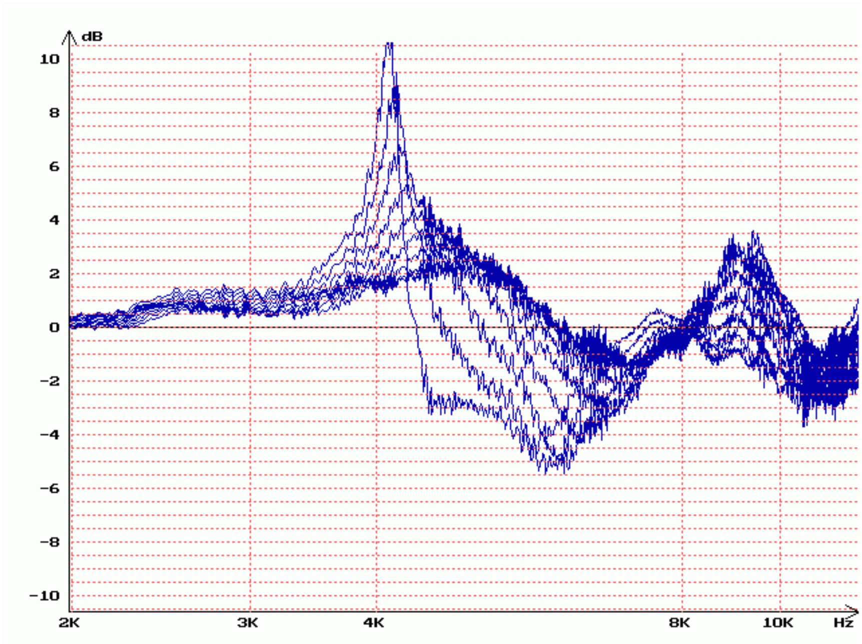
3. EFFECT OF THE ACOUSTICAL ENVIRONMENT NEAR TO THE HEAD

The HRTFDs are useful tools to search for differences between sets of HRTFs. They can be measured and calculated accurately and they are free from individual properties, showing only the effect of the modifications. This section presents the (acoustical) effect of objects near to head.

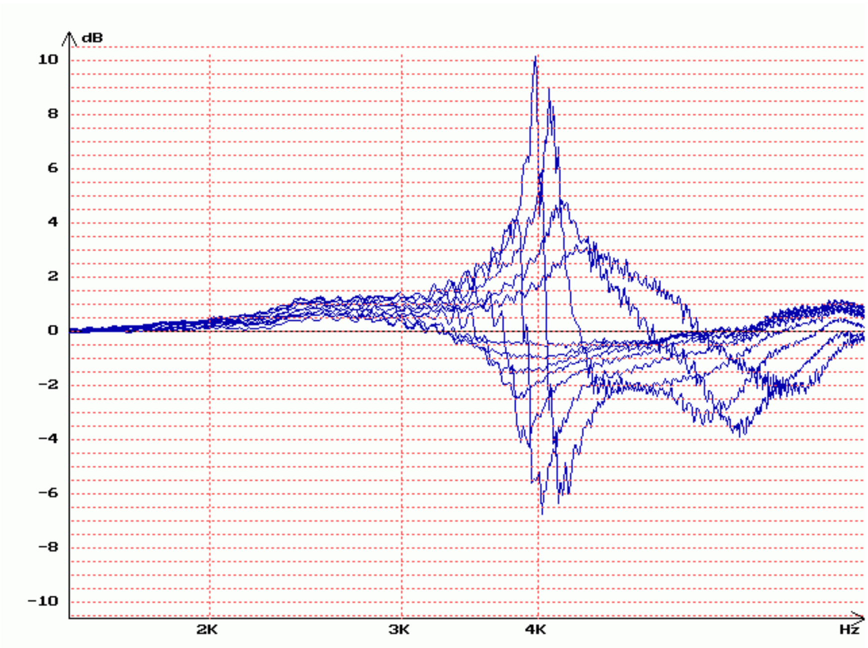
Dummy-head HRTFs were measured in 1° steps in the horizontal plane and 5° steps in the median plane from –10° up to +60° elevation. The objects we have been focused on are: four different kinds of glasses, four different but similar baseball caps and three toupees with different length and haircut. Moreover, some results we obtained from measurements with clothing. The short-cut hair toupee was placed always without covering the pinnae and the long-cut hair always completely covered the pinnae. This did not influence the results at all.

During the evaluation of the results we did not observe any significant differences among the different kinds of caps, toupees or glasses. These objects have common properties and thus common effects on the HRTFs, which are represented by the HRTFDs.

Figures 3–5 present some representative horizontal plane HRTFDs only as function of the frequency to show regular variations. We zoomed in to the interesting part of the frequency axis and so the plotted figures may have different x-axis scaling. Note the different scaling of the x and y-axis before comparing Figures 3, 4 and 5.

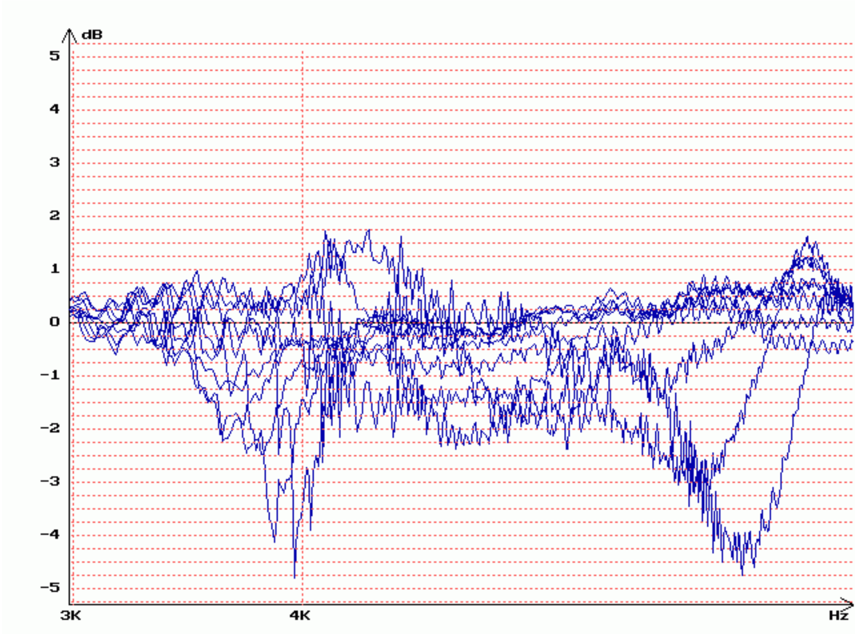


(a)



(b)

Figure 3. Horizontal plane HRTFDs as the function of frequency using hair: between $\varphi = 150°–195°$ in 5° steps (a) and between $\varphi = 80°–170°$ in 10° steps (b)



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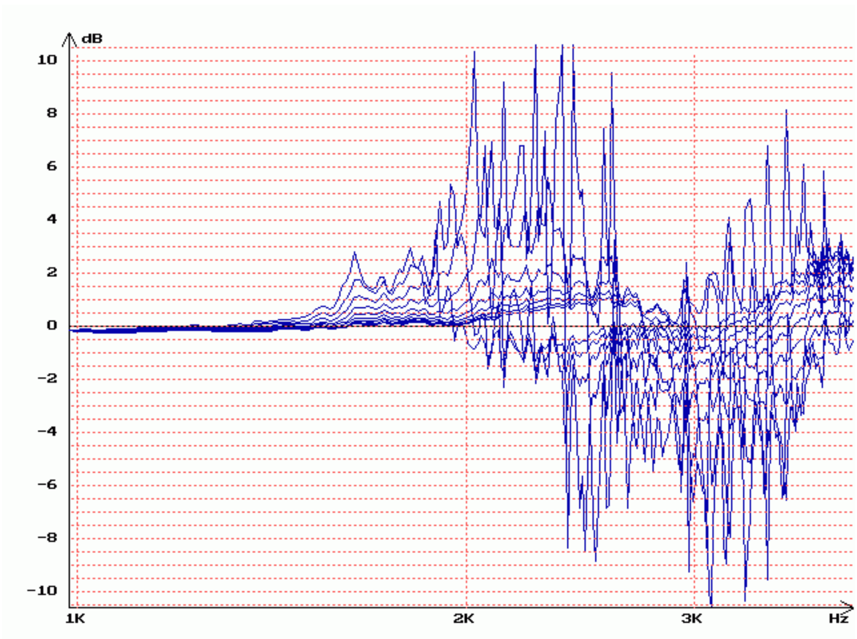
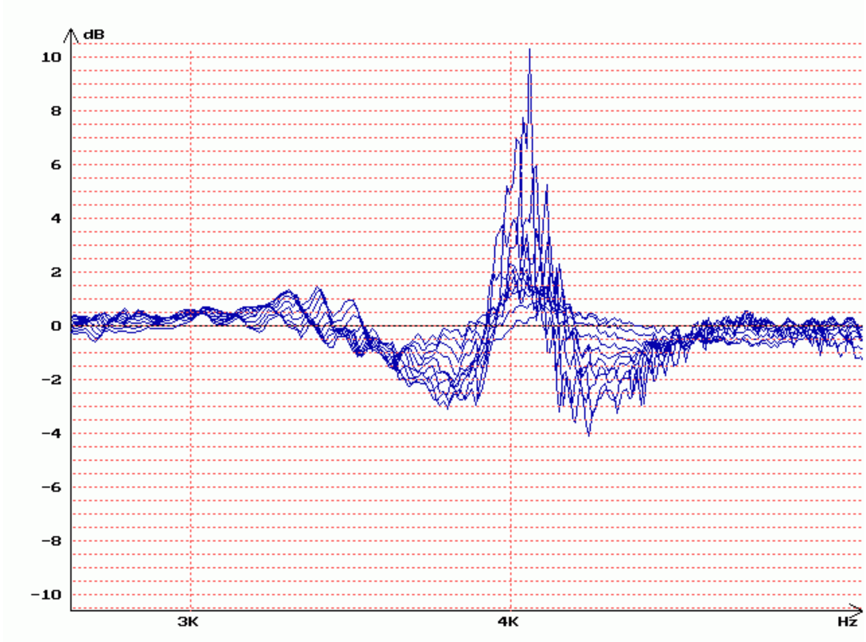


(b)

Figure 4. Horizontal plane HRTFDs as the function of frequency using baseball cap: between φ = 90°–170° in 10° steps (a) and between φ = 230°–260° in 2° steps (b)



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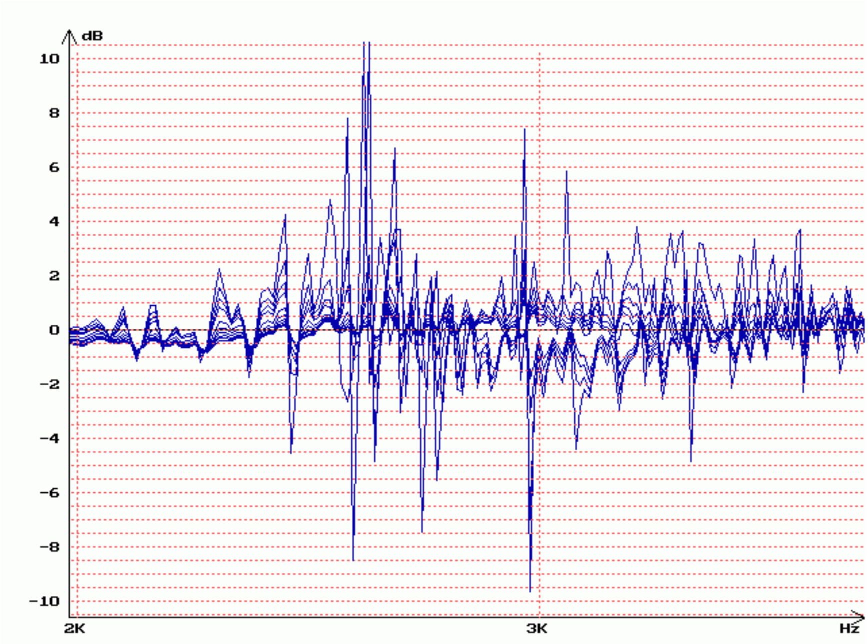


(b)

Figure 5. Horizontal plane HRTFDs as the function of frequency using glasses: between φ = 105°–150° in 5° steps (a) and between φ = 250°–270° in 2° steps (b)

Effect of the objects can be both amplification and damping, they influence the height of existing peaks and valleys of the HRTFs. As a general rule, we never found changes under 1500 Hz. Objects near to the head have different effects on frequency regions on the ipsilateral side and on the contralateral side. High-frequency components were affected at the closer ear and low-frequency “bright spots” – at the shadowed ear. These “bright spots” were found by Shaw e.g. at 1,9 kHz and 2,4 kHz [44]. The rigid spherical model of the head predicts amplifying effects near to the head due to diffraction even if the head directly blocks the contralateral ear [6, 39, 44–49]. This suggestion is supported by our measurements below 3 kHz.

3.1. Hair

Toupees are difficult to place onto the head symmetrical to the median plane. This may affects the left and the right ears’ HRTF different but we did not observe any significant difference in the measurement data. The evaluation was based on HRTFDs from 11 elevational positions, 1° horizontal steps and using three different haircuts. Hair produces a broadband and significant effect at 9, 10, and 11 kHz. The most important domain is between 4–5 kHz, where the differences are large as the source is moving in the horizontal plane independent of the elevational position. Fig. 3 shows representative horizontal plane HRTFDs. Hair produce deviations up to 16 dB at 4 kHz as the sound source moves between φ=150°–195° and φ = 80°–170° respectively.

At lower elevations (up to 20°) the 3,5-kHz component, at higher elevations (above 20°) the 2,5-kHz and the 2,8-kHz components are influenced as well. On the contralateral side differences up to 10 dB appear at the 1,8-kHz and 2,2-kHz bright spots. Above +30° elevation this effect is less significant. At +45° and +60° the deviations and the extent of the head-shadow area decrease, because the sound source is above the head.

3.2. Baseball cap

The same high-frequency components are mainly influenced (9, 10, 11 kHz) in the HRTFs of the closer ear. Fig. 4 shows representative horizontal plane HRTFDs. A baseball cap produce deviations of 5–7 dB at 3–4 kHz as the sound source moves between φ = 90°–170° and up to 20 dB between φ = 230°–260°. The same was observed up to +15° elevation.

Above +15° elevation the affected regions are divided into separate domains: from 3 kHz to 3,2 kHz and around 5 kHz. Because of the shadowing effect of the visor above +20° elevation, the HRTFs above 8 kHz are influenced the same way as in the head-shadow area (see Section 4). The components at 3–7, 9, and 12 kHz are mainly disturbed, but the head-shadow area itself is not influenced very much. The affected low-frequency components are 1,6 kHz; 1,8 kHz; 2,2 kHz and 2,5 kHz.

3.3. Glasses

The differences appearing at 9, 10 and 11 kHz and the changes at 4–5 kHz are less significant than by the use of caps and hair. Glasses are small, thin objects, they may influence the HRTFDs at higher frequencies. The elevational-depended components at 3,2 kHz and 3,5 kHz are reduced as the elevation increases. Fig. 5 shows representative horizontal plane HRTFDs. Glasses produce deviations of 14–16 dB around 4 kHz as the sound source moves between $\varphi = 105°–150°$ and at 2–4 kHz between $\varphi = 250°–270°$. The head-shadow area is not affected at all.

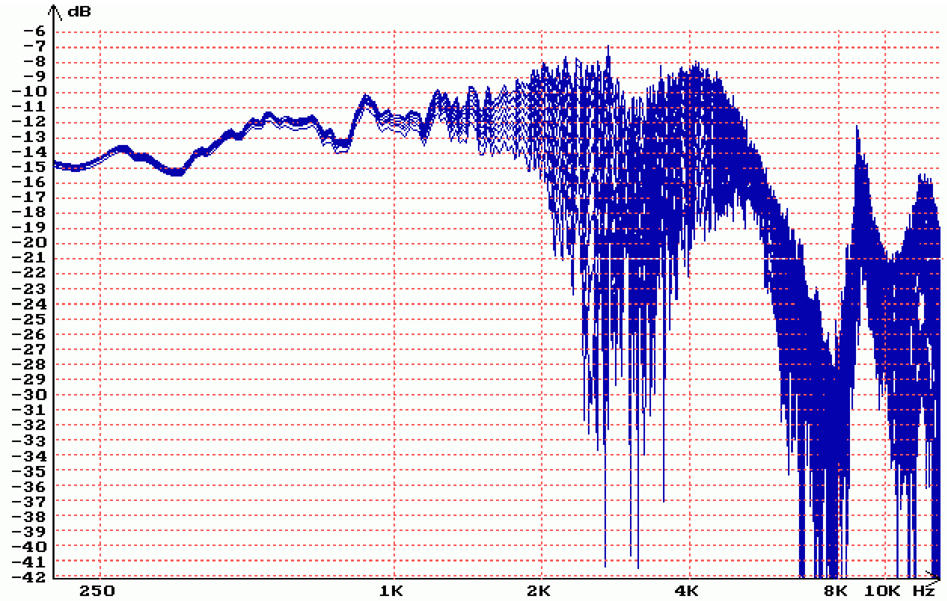
3.4. Clothing

Clothing has a common damping effect due to sound absorption. A thin T-shirt does not influence the transmission, but a thick shirt or coat has a damping up to 2–3 dB at 2–4 kHz, 3 dB at 8 kHz and 2 dB at 11 kHz. In the head-shadow area the low frequency components at 1,5 kHz; 1,8 kHz; and 2,5 kHz show +2 and +4 dB amplification. The same effect was observed by Tarnóczy [50].

4. THE HEAD-SHADOW AREA

The head-shadow area is on the contralateral side of the head. If a sound source is on the right side of the head, the left ear is shadowed by the head. Direct waves do not reach this ear, only reflected and diffracted sound waves. Geometrical calculations based on head size and wavelength can predict measurement data [40–43].

Figure 6 shows measured HRTFs and calculated HRTFDs from the head-shadow area. As expected, low frequency components are affected less than high frequency components: below 3000–3500 Hz there is less shadowing effect, but above this limit deviations up to 20 dB were measured. Because high frequency information is necessary for the localization, this disturbance leads to decreased localization performance (blur) on the contralateral side by monaural evaluation. Of course, by binaural evaluation interaural differences could be evaluated. Shadowing effect of simple geometrical forms and the dependence on the dimensions suggests that sound source occlusion has a low-pass filtering effect. The law of the first wavefront is valid and summing localization is performed [43]. The extent of the head-shadow area can be determined not only in frequency, but also as the function of magnitude and azimuth [1–4, 9, 24].



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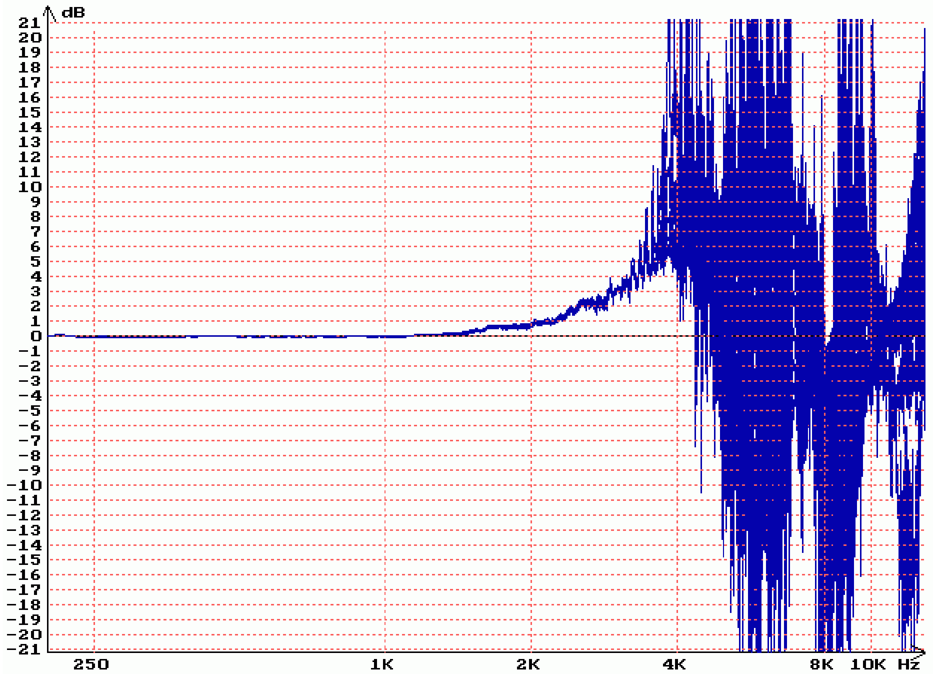

(b)

Figure 6. Ten measured dummy-head HRTFs (a) and calculated HRTFDs by re-measuring them (b) in the head-shadow area ($\varphi = 250°–260°$) in one degree steps

5. DISCUSSION

The HRTFs are influenced by the objects near to the listener's head. Small changes in the environment could cause large deviations in the entire frequency and spatial domain. These objects have determinable and measurable effects in most azimuthal directions. Glasses have the smallest effects, because they are thin and affect rather high frequency components. On the other hand, hair always has influence and baseball caps only in the region where shadowing effects occur. We assume that the most undesired effect for the hearing system is the extension of the shadowed area both in frequency and azimuth, because this can lead to localization errors by losing high frequency information. This low-pass filtering of sound source occlusion was observed both in free-field listening and HRTF reproduction based on the law of the first wave front [43]. Our everyday (non virtual) observation is that these changes in our HRTFs do not influence our localization performance significantly and we are not that sensitive to the fine structure of our own HRTFs.

Differences appear in the high frequency regions of the closer ear. At the same time, the HRTF of the contralateral ear will be influenced at lower frequencies. This results in an increased Interaural Intensity Difference. The directional information encoded in the sound waves will be evaluated by the closer ear in the high frequency regions and some lower frequency elements – by the contralateral ear.

6. CONCLUSION

With the help of an improved measurement system a database of about 40000 dummy-head HRTFs was recorded and evaluated in the frequency domain. The HRTFDs, defined as a quotient of HRTFs, are appropriate measures to find differences and changes in the fine structure of HRTF sets without the need for individual recordings. They can detect the existence of reflections, shadowing effects or regular variations caused by the acoustical environment near to head.

Objects near the head, such as caps, glasses, hair (etc.), affect the acoustical environment and they could have a clear and large influence on the HRTFs. High-frequency components on the ipsilateral side and low-frequency components are affected depending on elevation and azimuth.

This variation of the HRTFs apparently does not influence the localization performance and the quality of transmitted sound in our everyday life significantly. On the other hand, virtual audio synthesis with headphone playback needs individual and accurate HRTF reproduction.

Future works include listening tests with human subjects evaluating the measured HRTFs of the bare and of the dressed torso in order to determine the significance and measure of this variation on the localization performance during headphone playback in a virtual audio synthesis.

REFERENCES

[1] J. Blauert. Spatial Hearing. The MIT Press, MA, 1983.

[2] E. A. G. Shaw. Transformation of sound pressure level from the free-field to the eardrum in the horizontal plane. J. Acoust. Soc. Am. 1974, 56, 1848–1861.

[3] S. Mehrgart, V. Mellert. Transformation characteristics of the external human ear. J. Acoust. Soc. Am. 1977, 61, 1567–1576.

[4] D. Hammershøi, H. Møller. Free-field sound transmission to the external ear; a model and some measurement. Fortschritte der Akustik DAGA‘91, Teil A, Bochum, 1991, 473–476.

[5] C. B. Jensen, M. F. Sorensen, D. Hammershøi, H. Møller. Head-Related Transfer Functions: Measurements on 40 human subjects. Proceedings 6-th Int. FASE Conference, Zürich, 1992, 225–228.

[6] W. M. Hartmann. How we localize sound. Physics Today November, 1999, 24–29.

[7] D. J. Kistler, F. L. Wightman. Principal Component Analysis of Head-Related Transfer Functions. J. Acoust. Soc. Am. 1990, 88, 98.

[8] F. L. Wightman, D. J. Kistler. Headphone Simulation of Free-Field Listening I.-II. J. Acoust. Soc. Am. 1989, 85, 858–878.

[9] H. Møller, M. F. Sorensen, D. Hammershøi, C. B. Jensen. Head-Related Transfer Functions of human subjects. J. of the AES, 1995, 43, 300–321.

[10] D. Hammershøi, H. Møller. Sound transmission to and within the human ear canal. J. Acoust. Soc. Am. 1996, 100, 408–427.

[11] H. Møller, M. F. Sorensen, C. B. Jensen, D. Hammershøi. Binaural Technique: Do We Need Individual Recordings? J. of the AES, 1996, 44, 451–469.

[12] P. Maijala. Better binaural recordings using the real human head. Proceedings Inter-Noise 97, Budapest, Hungary, 1997, 1135–1138.

[13] H. Møller. On the quality of artificial head recording systems. Proceedings Inter-Noise 97, Budapest, Hungary, 1997, 1139–1142.

[14] H. Møller, D. Hammershøi, C. B. Jensen, M. F. Sorensen. Evaluation of artificial heads in listening tests. J. Acoust. Soc. Am. 1999,47, 83–100.

[15] E. M. Wenzel, M. Arruda, D. J. Kistler, F. L. Wightman. Localization using nonindividualized head-related transfer functions. J. Acoust. Soc. Am. 1993, 94, 111–123.

[16] J. C. Middlebrooks. Individual differences in external-ear transfer functions reduced by scaling in frequency. J. Acoust. Soc. Am. 1999, 106, 1480–1491.

[17] J. C. Middlebrooks. Virtual localisation improved by scaling nonindividualized external-ear transfer function in frequency. J. Acoust. Soc. Am. 1999, 106, 1493–1510.

[18] E. M. Wenzel, S. H. Foster. Perceptual consequences of interpolating head-related transfer functions during spatial synthesis. Proceedings of the ASSP Workshop on Applications of Signal Processing to Audio and Acoustics, New York, USA, 1993.

[19] H. Møller. Fundamentals of binaural technology. Applied Acoustics, 1992, 36, 171–218.

[20] P. Minnaar, S. K. Olesen, F. Christensen, H. Møller. Localization with Binaural Recordings from Artificial and Human Heads. J. Audio Eng. Soc. 2001, 49, 323–336.

[21] J. Blauert. Psychoakustik des binauralen Hörens. DAGA’84, Darmstadt, invited plenary paper, 117–128, 1984.

[22] J. C. Middlebrooks. Spectral Shape Cues for Sound Localization. Binaural and Spatial Hearing in Real and Virtual Environments, Lawrence Erlbaum Ass., Mahwah, New Jersey, 1997, 77–97.

[23] J. C. Middlebrooks, D. M. Green. Sound localization by human listeners. Ann. Rev. Psychol. 1991, 42, 135–159.
[24] M. Bodden, G. Canavet, J. Grabke, K. Hartung, T. Takahashi. Räumliches Hören in komplexen akustischen Umgebungen. Proceedings of DAGA'94, Bochum, 1994, 1137–1140.
[25] Gy. Wersényi. HRTFs in Human Localization: Measurement, Spectral Evaluation and Practical Use in Virtual Audio Environment. PhD Thesis, BTU Cottbus, Germany, 2002.
[26] Gy. Wersényi. Localization in a HRTF-based Minimum Audible Angle Listening Test on a 2D Sound Screen for GUIB Applications. AES Convention Preprint Paper, Nr.5902, Presented at the 115-th Convention, New York, New York, 2003 October, 10–13.
[27] J. Kawaura, Y. Suzuki, F. Asano, T. Sone. Sound localization in headphone reproduction by simulating transfer functions from the sound source to the external ear. J. Acoust. Soc. Japan, 1991, 12, 203–215.
[28] P. Damaske, B. Wagener. Richtungshörversuche über einen nachgebildeten Kopf. Acoustica, 1969, 21, 30–35.
[29] C. Jin, M. Schenkel, S. Carlile. Neural system identification model of human sound localization. J. Acoust. Soc. Am. 2000, 108(3), 1215–1235.
[30] N. Cheung, S. Trautman, A. Horner. Head-Related Transfer Function Modeling in 3-D Sound Systems with Genetic Algorithms. J. Audio Eng. Soc. 1998, 46(6), 531–539.
[31] D. R. Begault, E. Wenzel, M. Anderson. Direct Comparison of the Impact of Head Tracking, Reverberation and Individualized Head-Related Transfer Functions on the Spatial Perception of a Virtual Speech Source. J. of the AES, 2001, 49(10), 904–917.
[32] P. Berényi, A. Illényi. What does it mean for an HRTF not to have the minimal phase property? Proceedings of Inter-Noise 96, Liverpool, England, 1996, 2127–2130.
[33] D. J. Kistler, F. L. Wightman. A model of head-related transfer functions based on principal components analysis and minimum-phase reconstruction. J. Acoust. Soc. Am. 1991, 91, 1637–1647.
[34] Gy. Wersényi. Measurement system upgrading for more precise measuring of the Head-Related Transfer Functions. Proceedings of Inter-Noise 2000, Nice, France, 2000, 1173–1176.
[35] A. Illényi, Gy. Wersényi. Discrepancy in binaural tests and in measurements of sound field parameters. Proceedings of the International Békésy Centenary Conference on hearing and related sciences, Budapest, Hungary, 1999, 160–165.
[36] Gy. Wersényi, A. Illényi. Test Signal Generation and Accuracy of Turntable Control in a Dummy-Head Measurement System. J. of the AES, 2003, 51(3), 150–155.
[37] Gy. Wersényi, P. Tatai. Detection of reflections in free-field directional hearing by waveform analysis of accurate dummy-head HRTFs. Proceedings of IEEE Instrumentation and Measurement Technology Conference, Budapest, Hungary, 2001, 606–609.
[38] K. A. J. Riederer. Computational quality assessment of HRTFs, EUSIPCO(X) – European Signal Processing Conference, Tampere, Finland, 2000.
[39] C. I. Cheng, G. H. Wakefield. Introduction to Head-Related Transfer Functions (HRTFs): Representations of HRTFs in Time, Frequency, and Space. J. of the AES, 2001, 49, 231–249.
[40] K. Genuit. Untersuchungen zur Bedeutung von einzelnen Strukturen der Außenohrübertagungs-funktion und das räumliche Hören. DAGA'86, Oldenburg, 1986, 485–488.
[41] K. Genuit. Eine systemtheoretische Beschreibung des Außenohres. DAGA'85, Stuttgart, 1985, 459–462.

[42] K. Genuit. Ein kalibrierfähiges Kunstkopf Mess-System. DAGA'84, Darmstadt, 1984, 279–282.
[43] H. Farag, J. Blauert, O. A. Alim. Psychoacoustic Investigations on Sound-Source Occlusion. Journal of the AES, 2003, 51(7/8), 635–645.
[44] E. A. G. Shaw. The external ear. Handbook of Sensory Physiology 1, Auditory System, Anatomy Physiology Ear. Springer, New York, 1974.
[45] D. S. Brungart, W. M. Rabinowitz. Auditory localization of nearby sources. Head-related transfer functions. J. Acoust. Soc. Am. 1999, 106(3), 1465–1479.
[46] M. B. Gardner, R. S. Gardner. Problem of localization in the median plane: effect of pinnae cavity occlusion. J. Acoust. Soc. Am. 1973, 53, 400–408.
[47] B. G. Shinn-Cunningham, S. Santarelli, N. Kopco. Tori of confusion: Binaural localisation cues for sources within reach of a listener. J. Acoust. Soc. Am. 2000, 107(3), 1627–1636.
[48] G. F. Kuhn. Model for the interaural time differences in the azimuthal plane. J. Acoust. Soc. Am. 1977, 62, 157–167.
[49] V. R. Algazi, C. Avendano, R. O. Duda. Elevation localization and head-related transfer function analysis at low frequencies. J. Acoust. Soc. Am. 2001, 109, 1100–1122.
[50] T. Tarnóczy. Über den Verstärkerungs-Verminderungs-Effekt der Ohrmuschel und des Kopfes. Proceedings 6th Int. FASE Conference, Zürich, 1992, 229–232.
[51] K. Genuit, H. J. Platte. Untersuchungen zur Realisation einer richtungsgetreuen Übertragung mit elektroakustischen Mitteln. Proceedings of DAGA'81, Berlin, 1981, 629–632.