Spatial hearing as a function of growth: how adults differ from children

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Spatial hearing, and how we hear noise and sound, is strongly dependent on our individual head-related transfer functions (HRTF). In order to obtain spatial noise measures artificial heads are used. Spatial cues, such as the interaural time and level differences can be deduced from the HRTF.

The first varies a lot depending on the head width and whether the effect of the second cue is more complex. Many investigations showed that there exist numerous individual differences between the HRTFs of adults caused by the differences in the head geometries.

It becomes evident that children and adults differ tremendously as far as their respective head-related transfer functions are concerned. Differences in the anatomy of children and adults thus result in different binaural cues. The individual anthropometric parameters, however, affect the binaural cues to a varying extent.

These new findings open up new possibilities to develop artificial child heads and couplers for hearing aids that are suitable for children.

INTRODUCTION

It is well known that the HRTFs of different individuals vary significantly (Møller *et al.*, 1995) due to the anthropometric data of the subjects. A direct relation between the growth and details of HRTF has not yet been established. When it comes to differences between adults and children, the anthropometric parameters of the head and torso differ to a much greater degree than among adults. The parameters describing the head, torso and pinna differ in terms of their growth-dependency.

The objective of this contribution is to get a first overview in the frequency range up to 8 kHz, which is sufficient for audiological applications of diagnosis and therapy.

SIMULATION OF THE HRTF WITH THE BOUNDARY ELEMENT METHOD

Since HRTFs measurements of children or infants are not possible, a different method is used to obtain the HRTF.

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CAD models of heads were created and used to calculate the HRTFs using the Boundary Element Method (BEM). The acquisition of anthropometric data was made with a photogrammetric system. As written in detail in (Fels et al., 2004) and (Fels, 2008), stereo photographs have been taken from the test subjects. A digital photogrammetric system – PHIDIAS (Benning and Schwermann, 1997) is used to evaluate the three-dimensional photographs.

In this study, the blocked meatus (ear canal entrance) is chosen as the reference point because it offers many advantages, especially as a clear reference condition. The results can be compared and discussed more easily since influences from the ear canal can be excluded. The well-defined interface for an artificial ear for children, which is currently in development is another advantage.

According to the definition of HRTF, the sound pressure at the reference point is divided by the sound pressure (plane wave in the far field) without the listener. The direct simulation of this method would require an immense computer capacity as every angle of sound incidence must be simulated. The situation, however, can be replaced by a reciprocal arrangement (Lyamshev, 1959; Shaw, 1976). Source and receiver can be exchanged according to reciprocity.

For the BEM processing software developed at the Institute of Technical Acoustics (RWTH Aachen University) is used programmed in MATLAB. The pressure is solved for frequencies from 100 to 8000 Hz in steps of 100 Hz.

During the post processing phase field points can be created and the sound pressure can be calculated at these field points. This means that the sound pressure for a far-field detector surface containing several points can be calculated quickly. Consequently, the head-related transfer functions can be computed according to Eq. (1).

$$\mathrm{HRTF}(\vartheta,\varphi)=\frac{p(r,\vartheta,\varphi)}{\mathrm{j}\omega\rho_0 Q\mathrm{e}^{-\mathrm{j}kr}/(4\pi r)} \qquad \text{(Eq. 1)}$$

with HRTF (ϑ, φ) denoting the head-related transfer function for a specific direction in polar angular direction ϑ and azimuthal direction φ, $p(r, \vartheta, \varphi)$ the sound pressure obtained at the far field point in the specific direction and distance r, ω the angular frequency, ρ_0 the equilibrium density of air, Q the volume velocity of the radiation area at the ear canal entrance and k the wave number. The denominator represents the difference between sound radiation and sound reception in terms of the low-frequency law, thus correcting the radiation impedance in the reciprocal approach.

This approach has been verified by simulating several heads in the reciprocal arrangement compared with measurements of the same head in the ordinary way (non reciprocal). A wooden model was built according to the simulated CAD model and the measured results showed good agreement with the simulated results (cf. Fels et al., 2004).

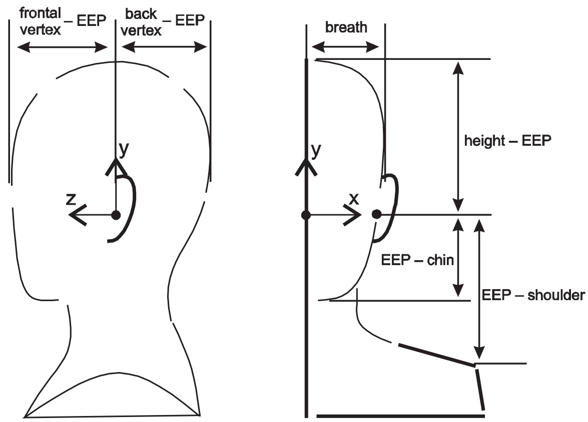

Fig. 1: Six anthropometric parameters describing roughly a head.

PARAMETER STUDIES ON THE HEAD AND TORSO GEOMETRY AND ITS EFFECTS ON THE HRTF

The database consists of 95 subjects aged six months to 17.5 years and over 40 anthropometric measurements of each subject describing the head and torso (ref. Fels, 2008). The growth-dependency can be studied for each parameter.

In order to investigate the influence of the head and torso geometry, this paper focuses on six important anthropometric parameters describing roughly a head: the distance from the shoulder to the ear (measured from the ear canal entrance point (EEP)), the frontal vertex (forehead), the back vertex, the breadth of the head, the height of the head, and the distance from the chin (lowest point) to the EEP. Figure 1 shows the six parameters. With the help of these parameters it is possible to construct a simplified model of the head.

Table 1 shows these values and their ranges. To evaluate the highest point on the top, or the breadth, for example, the vertex of the radii measured on the heads was taken. Since this table shows the maximum and minimum values as well, the range of the parameters during growth is visible. The distance from ear to shoulder varies most of all. Additionally, the 5% and 95% quantiles are calculated.

	minimum	5% quantile	mean	median	95% quantile	maximum
distance ear to shoulder	26 mm	43 mm	99 mm	99 mm	138 mm	157 mm
breadth	53 mm	64 mm	76 mm	76 mm	86 mm	97 mm
chin	44 mm	52 mm	72 mm	72 mm	91 mm	102 mm
top of the head	106 mm	115 mm	131 mm	132 mm	141 mm	150 mm
vertex front	42 mm	70 mm	86 mm	87 mm	98 mm	108 mm
vertex back	69 mm	81 mm	98 mm	98 mm	114 mm	117 mm

Table 1: Parameter variations of the anthropometric data of the head and torso investigated. Values refer relatively to the center of the head.

When comparing these three head sizes, 5% and 95% quantile and median, with the database, several turned out to match with the actual head sizes of subjects from the above-mentioned database. The 5% quantile head is equivalent to that of a 6-month-old infant, the median head is equivalent to that of a six-year-old child, and the 95% head to that of a sixteen-year-old teenager. Using these 6 values (and their corresponding radii), it is possible to create simplified models of the head and torso. The model heads were all constructed without a pinna as only the influence of the six most important head parameters will be investigated in this section. The influence of the pinna will be discussed in greater detail in the second part of this paper.

Parameter variations of the head and torso geometry

First of all, the median head was built with the help of the database. The purpose of creating a median head was to produce a head based on all values that reflect all dimensions in the middle of the growth.

On this basis the geometric measurements can be varied and extended to smaller and larger values. This median head is not intended to represent the "best head" or the like.

The head-related transfer functions were calculated using BEM at a distance of 2 meters according to Eq. (1).

While using the median head only one parameter was varied at a time (to the 5% respectively 95% quantile value) to analyze the influence of the individual parameters on the HRTF.

All other parameters were not changed. 12 CAD models, each one differing from the median head in one single parameter only, were created using this approach.

In order to highlight the influence of each parameter on the HRTF, the differences of the HRTF magnitude between the median head and the head with the changed parameter are calculated ($|HRTF_{head1}| - |HRTF_{head2}|$) for all angles of incidence and frequencies. Examples of these differences are plotted in Fig. 2. The gray values indicate the dB-value of the HRTFs – bright values are positive and dark values are negative.

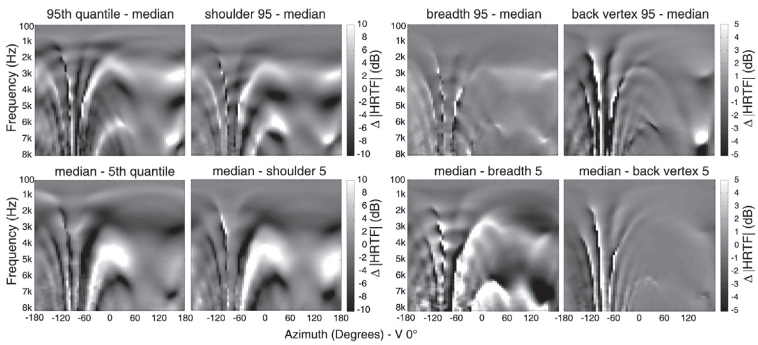

Fig. 2: Differences in the HRTF caused by changes in the head and torso geometry in dB. Each panel shows the difference between the head with the altered value and the median head in the horizontal plane. In case of the heading "quantile" all parameters are changed.

In the very left column of Fig. 2 we see the difference in the magnitude of the HRTF for the heads whose parameters are all changed. The difference between a median and the 5%-quantile and the 95%-quantile – heads, respectively can clearly be seen.

It is of particular importance to notice the influence of the distance between the ear and the shoulder. The differences triggered by this parameter are almost as large as the differences in the results of all 5%- and 95%-quantile heads.

Furthermore it can observed that the breadth of the head and the back vertex have an enormous influence as well (the gray values range from –5 dB to +5 dB). Other parameters such as the chin or the height of the head have little influence on the HRTF.

The assessment of the variations of all head dimensions and of the impact they have on details in the HRTF is a complex challenge. Therefore a difference measure in Eq. (2) is used to summarize the results.

$$\text{difference measure} = \frac{\sum \left|\text{difference values [dB]}\right|}{\text{number of values}} \qquad \text{(Eq. 2)}$$

The differences for certain calculated planes are thus converted into a single-number value. A higher value signifies a high average deviation and a lower value signifies a low average deviation.

For each plane the difference measure is calculated once for the difference between the head where the parameter was changed to the 95%-quantile value and the median, and once for the difference between the median head and the head where the parameter was changed to the 5%-value.

The parameter "distance between shoulder and ear" has the largest influence on the HRTF. It is interesting that this parameter is also the one that varies most during growth (cf. Table 1). When it comes to larger heads (95% median, e.g. 16-year-olds – 6-year-olds) the back vertex has a strong influence on the HRTF. The breadth of the head plays a more important role for smaller heads (median – 5%). All other parameters have only little influence on the HRTF (cf. Table 3).

PARAMETER STUDIES ON THE PINNA GEOMETRY AND ITS EFFECTS ON THE HRTF

For the study described above all CAD models of heads are built without a pinna. In this section the influence of anthropometric pinna parameters will be discussed.

The size, position and orientation of the pinna in relation to the head are measured with the photogrammetric system. A second coordinate system is defined, so that various pinnae can be compared despite different head sizes and shapes. The ear canal entrance is defined to be the origin of the pinna coordinate system.

	minimum	5% quantile	mean	median	95% quantile	maximum
breadth (pinna)	17.9 mm	23.0 mm	28.9 mm	28.7 mm	33.9 mm	37.6 mm
height (pinna) up. vertex	17.8 mm	23.9 mm	29.2 mm	29.2 mm	34.9 mm	40.0 mm
height (pinna) low. vertex	14.5 mm	19.2 mm	24.1 mm	24.1 mm	29.6 mm	31.1 mm
breadth (cavum conchae)	12.7 mm	13.3 mm	18.0 mm	18.4 mm	24.3 mm	30.1 mm
height (cavum conchae)	12.2 mm	16.0 mm	21.6 mm	21.5 mm	26.1 mm	28.7 mm
depth (cavum conchae)	4.3 mm	6.3 mm	9.6 mm	9.8 mm	13.8 mm	16.3 mm

Table 2: Parameter variations of the anthropometric data of the pinna investigated. Values refer relatively to the pinna coordinate system.

In this study a simplified model for the head shape was in use. The same applies for the pinna. The simplified (geometric) pinna is sufficient for frequencies below 6–8 kHz. The outer pinna is simplified in a plane area.

The height and the breadth of the ear, the upper and lower radii and the height, breadth and depth of the cavum conchae are measured from the photographs and stored in a database. The rotation of the ear is calculated with the help of the two coordinate systems. All the pinna data refer to this pinna coordinate system.

All ear parameters except the rotation of the ear show a strong growth dependency. Table 2 shows these most important parameters and their range of values. The rotation of the ear is not displayed because of its different unit. The parameter changing most during growth is the ear height.

Parameter variations of the pinna geometry

Based on the median head with a median pinna, all ear parameters are changed individually to the lower and upper values in the database.

The difference of the HRTFs of an ear with changed value and the median pinna was evaluated to highlight the effect on each parameter on the HRTF. Figure 3 shows these differences with regard to several parameters. In each case the parameters are changed to the value according to Table 2.

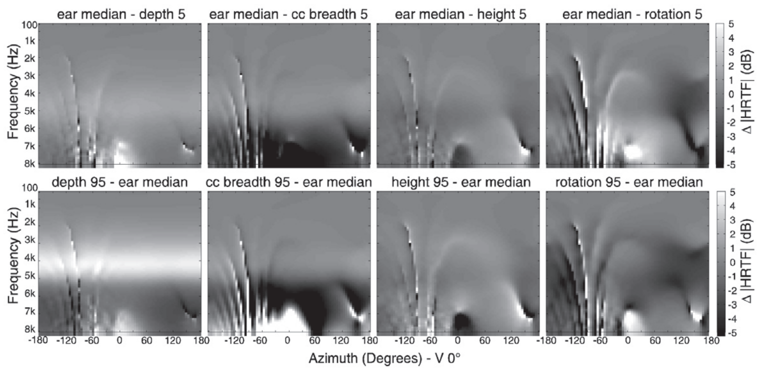

Fig. 3: Differences in the HRTF caused by changes in the pinna geometry in dB. Each figure shows the difference between the head with the altered value and the median pinna in the horizontal plane.

In case of the depth which should have been changed to the 5%-quantile value, the CAD model could not be created as the median head with a median ear turned out to be too large so that the depth with such a value could not be constructed. Therefore the smallest depth available for the CAD model was taken into account. However, this produces an enormous difference, too.

The different plots show clearly that the pinna causes almost no influence up to 2 kHz. This is, however, as expected since the wavelength is too long to be influenced by the pinna. A significant difference can be seen above frequencies of 3 kHz.

Once again the difference measure according to Eq. (2) is calculated to summarize the effects on the HRTF. Table 3 shows the results for the parameter variations of the pinna.

The breadth and the depth of the cavum concha and the rotation of the ear have the strongest influence on the HRTF. The height and the breadth of the pinna on the other hand turn out to have only little influence even though these parameters vary most of all. Regarding the depth of the cavum conchae it is expected that this variation causes a direction independent effect in the frequency range of 4 kHz.

head and torso geometry	pinna geometry
+ big influence ▪ distance between shoulder and ear ▪ breadth of the head ▪ back vertex – small influence ▪ height of the head ▪ chin ▪ frontal vertex	+ big influence ▪ Cavum Conchae breadth and depth ▪ rotation of the ear – small influence ▪ height of the ear ▪ breadth of the ear

Table 3: Classification of the anthropometric data according to the influence on the HRTF.

SUMMARY AND CONCLUSION

The results presented here show clearly which anthropometric parameters influence the HRTFs during human growth. The anthropometric data of 95 subjects aged 6 months to 17.5 years were measured. A statistical evaluation of this data was conducted. On the basis of these results six parameters describing a head (breadth and height of the head, front and back vertex, chin and distance between the ear and the shoulder) and six parameters describing a pinna (breadth and height of outer ear and cavum conchae, depth of the cavum conchae, and rotation of the ear) have been studied with regard to their influence on the HRTF.

CAD models based on the median data of the database, the 5%-quantile-values, and the 95%-quantile-values were built. Moreover models were created differing from the median head respectively the pinna only in terms of one parameter. This parameter was changed to the 5 or 95%-quantile-value. The HRTFs of the heads were computed with a BEM solver between 100 to 8000 Hz. First of all, the results show how different the HRTFs turn out to be between a very young child and an older person. Furthermore the results show clearly which parameter brings about which kind of change.

For the head and torso geometry it turned out that the most important parameter with regard to differences in the HRTF is the distance from the ear to the shoulder. It is shown that the breadth of the head and the back vertex have immense influence as well. Only a very slight influence may be attributed to the height of the head, the chin, and the frontal vertex.

For the pinna geometry the parameter varying most of all during growth, i.e. the height of the ear, turned out to have only very little influence on the HRTF and the computed interaural level difference. The greatest influence has to be attributed to the depth and the breadth of the cavum concha.

The influence of the parameters described above, are tested independently from each other as far as possible. This kind of procedure is only an attempt to categorize the influence of the growth, however, it is not an orthogonal parameter system.

By varying one parameter at a time, only an indication is determined. The results, however, are clear and reasonable, which makes it possible to use them as a basis for further studies or applications.

The most important anthropometric data is thus available and can be used for future experiments featuring dummy heads and dealing with the special requirements with regard to children.

Moreover, the data will be of relevance with regard to new standards for dummy heads.

Although the results all have a computational character with certain boundary conditions (symmetric geometry, hard surfaces, etc.) and even though a psychoacoustic part is not included, the results can be used as a basis for further studies. One important task will be the re-evaluation of standard artificial heads. The influence of the specific dimensions allows a well-defined procedure of data mining with focused uncertainty budgets. Further studies and psychoacoustic experiments will be conducted to create artificial heads for children and adults.

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