INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2022, VOL. 68, NO. 2, PP. 193-200
Manuscript received February 28, 2022; revised April, 2022. DOI: 10.24425/ijet.2022.139867

Estimation of Asymmetry in Head Related Transfer Functions

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***Abstract*—The individual Head-Related Transfer Functions (HRTFs) typically show large left-right ear differences. This work evaluates HRTF left-right differences by means of the rms measure called the Root Mean Square Difference (RMSD). The RMSD was calculated for HRTFs measured with the participation of a group of 15 subjects in our laboratory, for the HRTFs taken from the LISTEN database and for the acoustic manikin. The results showed that the RMSD varies in relation to the frequency and as expected is small for more symmetrical HRTFs at low frequencies (0.3÷1 kHz). For higher frequency bands (1÷5 kHz and above 5 kHz), the left-right differences are higher as an effect of the complex filtering caused by anatomical shape of the head and the pinnae. Results obtained for the subjects and for data taken from the LISTEN database were similar, whereas different for the acoustic manikin. This means that measurements with the use of the manikin cannot be considered as perfect average representation of the results obtained for people. The method and results of this study may be useful in assessing the symmetry of the HRTFs, and further analysis and improvement of how to considered the HRTFs individualization and personalization algorithms.**

***Keywords*—acoustics; sound processing; virtual reality; spatial sound; Head Related Transfer Functions**

I. Introduction

HEAD Related Transfer Functions (HRTFs) or Head Related Impulse Responses (HRIRs) are widely used in multimedia and telecommunication systems, which employ technology of virtual or augmented reality. The HRTFs or equivalently HRIRs represent a pair of filters used in the headphone listening that allow to convert monaural signal into left and right binaural signals whose temporal and spectral properties possibly contain all cues used by the listener to locate the sound source in three-dimensional space. The natural filtering effect in the binaural listening is a result of the presence of the pinnae, head, and torso in the acoustic field. This is represented in the measured or modelled HRTFs. As the most pronounced effect is created by pinnae shape the HRTFs possesses highly individual characteristics depending on the individual anthropometrical features [1-4]. Thus, the HRTFs for a given person provide best listening result when used by this person. It is known that employing a non-personal HRTFs results in increased error rate in sound source localization [1-4].

Recent studies on HRTF try to find a method to assess the similarities between the filters, either dealing with numerical data or in the relation to results of listening tests. To evaluate the left-right symmetry of the HRTFs Zhong et al. [8] defined a normalized left-right cross-correlation functions and a left-right symmetry coefficients in frequency bands corresponding to the equivalent rectangular bandwidths (ERBs) that represent the filtering in the human auditory system. In the horizontal plane, in condition in which the sound source was on the same side as the ear measured, the symmetry was greater and existed up to 5 kHz than in condition in which the sound source was on the opposite side to the ear measured in which symmetry was seen only up to 1 kHz. In median plane, a noticeable asymmetry was found above 6 kHz.

Jo et al. [7] assessed the HRTFs differences for data from CIPIC [5] database using Euclidian distance metric to compare spectral differences wideband and in 1/3-octave frequency bands. The data showed large variability that occurred for the front and back sound source positions. Such a variability in HRTFs was smaller for sound sources at high elevation angles.

Genovese et al. [9] calculated the interaural time differences from the HRIRs taken from four major HRTF databases. The work assessed the variability in horizontal and vertical planes, finding largest differences of about 90 μs at the horizontal angle of 110° decreasing with the elevation angle.

In this study, a measure called the Root Mean Square Difference (RMSD) is introduced (Section II) and used to describe the similarity between left and right HRTFs. Data taken into account include the HRTFs acquired in our laboratory, taken from the HRTF LISTEN database [6], and measured with the use of the Brüel and Kjær 4100-D acoustic manikin.

II. The RMSD Measure

A Root Mean Square Difference (RMSD) introduced here is a RMS measure of the difference between amplitude-frequency responses seen in the left and right HRTFs summed over all considered spectral bands. Correspondingly large or small values of the RMSD are associated with large or small overall difference between HRTFs for left and right ear in the considered frequency range. The exact formula is shown by (1):

$$RMSD = \frac{1}{\sqrt{N}} \sqrt{\sum_n [HRTF_{L,n}(f) - HRTF_{R,n}(f)]^2}, \qquad (1)$$

where:

n is the specific frequency point or frequency band,
$HRTF_L$ and $HRTF_R$ are functions for the left and right ear,
N is the number of frequency points or frequency bands in the considered frequency range.

This work was supported by the grant from Scientific Council for the Discipline of Automatic Control, Electronics and Electrical Engineering.

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Depending on frequency resolution applied to the HRTF the frequency point can be understood as the FFT point on linear frequency scale. The frequency resolution depend on the length of the HRIR, that is not a standardized value for HRTFs dataset. The sum over 1 to N depends on the frequency range for which the RMSD is calculated. Similar approach was used in our previous studies [10,11].

III. HRTF DATA

Three sets of data were analyzed in our study. The first set originated from measurements performed in our laboratory (WUT data) with a participation of a group of 15 subjects [10,11]. The second set of data comprised 50 HRTFs taken from the LISTEN database [6]. The third set of data were measurements done in our laboratory with the use of a Brüel and Kjær 4100-D acoustic manikin (head and torso simulator). Details related to sets of data are shown in Table 1.

A. *WUT HRTF data and manikin measurements*

In the measurement setup used in our laboratory, the subject was seated on a stool in front of a sound source fixed in its position. The subject was rotated clockwise with the use of Brüel and Kjær type 3921 turntable. Continuous rotation with appropriate averaging time led to data obtained with required resolution of 10° in horizontal angle. The sound source included 10 wideband GD 12/8/2 loudspeakers positioned 1.5 m from the subject's head (midpoint) on a vertical arc from -45° to 90° elevation with spacing of 15°. The 0° elevation was set relatively to the horizontal plane defined at the height of the midpoint of the subject's head. Capturing a whole set of HRTF pairs required 10 rotations of the subject with switching among all vertically positioned loudspeakers.

TABLE I
COMPARISON OF WUT DATA, MANIKIN MEASUREMENTS, AND HRTF LISTEN DATABASE USED IN THIS STUDY [6,10,11]

Feature	WUT data and HATS	LISTEN database
Number of subjects	15 + B&K 4100-D	50
HRTF pairs	370	187
Horizontal resolution	15°	15°
Vertical resolution	10°	15°, 30°, and 60° [a]

[a] Depending on horizontal angle

The frequency responses were recorded at the entrance to blocked ear canal with the use of a pair of the Brüel and Kjær type 4101 miniature microphones. To acquire the HRTF data the Maximum Length Sequence (MLS) signal was used generated and recorded by the Brüel and Kjær PULSE system.

The data were gathered for 15 subjects, 4 women and 11 men, aged 19-29 years, who participated voluntarily in the study. For each subject, the HRTFs were recorded for 370 sound source locations, that included 36 azimuthal angles (0° angle and angles from 5° to 355° in 10° steps) and 10 elevation angles (from -45° to 90° in 15° steps).

The data for Brüel and Kjær 4100-D manikin were gathered in a similar way. The manikin was positioned on the stool in the place of the human subject. This same Brüel and Kjær type 4101 microphone set was used to record the signal (not the internal manikin microphones).

B. *LISTEN HRTF database*

The publicly available LISTEN database of IRCAM [6] includes HRIRs taken from 51 subjects. For each subject, 187 HRIR pairs are available at 10 evenly spaced elevation angles, ranging from -45° to 90° in 15° steps. Correspondingly, data in horizontal angles (from 0° to 360°) have a resolution of 15°, 30°, and 60°, respectively for the elevation angles -45°÷45°, 60°, and 75°. A single HRIR pair is taken at the 90° elevation angle.

The LISTEN database was chosen for a comparison with our data as its structure uses similar angles in the vertical plane. Out of 51 subjects data of 50 were considered. One subject was excluded as results were detected to be flawed by artifacts, which was also noted by Genovese et al. [9].

IV. CONDITIONS

The way the pinna reflections create signal delays added to the first wavefront and in effect shapes of the pinna related localization filter is strongly dependent on either direct exposure to the sound source (the sound source facing the ear) or shadowing the sound source by the head (the sound source positioned on the opposite head side than the ear). For this reason, reasonable assessment of the left and right ear HRTFs asymmetry by means of the RMSD values should take into account these two different geometries. and treat separately the ears exposed to the sound source or shadowed by the head. In the following analysis two conditions, regarding the placement of the sound source in relation to the ears, were selected specifically, as follows:

1. 'L' condition (light condition) - the ears directly exposed to the sound source (right ear with sound source on the right compared to the left ear with the sound source on the left in relation to the head), see Fig. 1a.
2. 'S' condition (shadowed condition) - the sound source shadowed by the head (right ear with sound source placed on the left head side compared to the left ear and the sound source placed on the right side), see Fig. 1b.

Similar geometrical conditions were selected by Jo et al. [7].

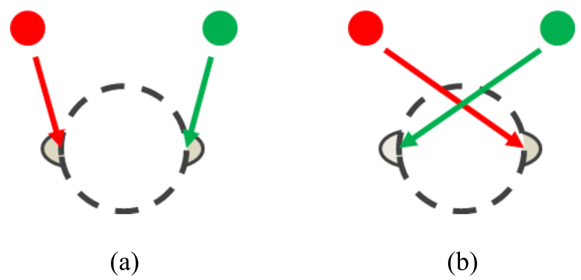

Fig. 1. Schematic representation of conditions for asymmetry comparison: (a) both ears facing the sound source; the 'L' (light) condition, (b) the sound source shadowed by the head, the 'S' (shadowed) condition

The data were analyzed by splitting the audible frequency range into three frequency bands chosen as 0.3÷1 kHz, 1÷5 kHz, 5÷10 kHz. Regarding the sound wavelength, different anatomical structures impose an effect on the sound incoming to the ear canal and thus on the HRTF [1,2], as follows: both head and the torso (below 1 kHz), head and pinnae (1÷5 kHz), and pronounced effect of the pinnae (above 5 kHz).

V. RESULTS

The RMSD measure in all conditions considered is split among Figs. 2, 3 and 4 along the elevation angles. Figs. 2 and 3 represent fairly frontal elevation angles of 0°÷45° and -45°÷0°. Figure 4 displays results for high elevation angles of 45°÷90°. All figures use the same layout. Results for WUT data, LISTEN database and Brüel and Kjær 4100-D manikin are shown in upper, middle, and lower rows, respectively. The three frequency ranges of 0.3÷1 kHz, 1÷5 kHz, and 5÷10 kHz are shown, respectively, in the left, middle and right column. In each panel, the RMSD is shown by two polar plots in a form of semicircles with ears facing the sound source (L condition) on the left and the sound source shadowed by the head on the right (S condition), conditions as depicted in Fig. 1. Various elevation angles are represented by different lines as described in the figure legend.

As expected, the lowest RMSD values occur for frequency band 0.3÷1 kHz in Figs. 2, 3, and 4 (left column). For the WUT data and elevation angles 0°÷45° (Fig. 2, upper left panel), the variability of the RMSD with horizontal and elevation angles in the L condition is very small, about 1 dB or less. Variability in the S condition is larger but not exceeding 2.5 dB. The largest value occurs at 135° horizontal angle, but only for the elevation angle of 15° or 30°. The RMSD decreases for 45° elevation angle.

For the LISTEN database (Fig. 2, middle left panel) the RMSD in the L condition is much like for the WUT data. In the S condition, differences represented by the RMSD at 135° horizontally are more pronounced amounting to about 4 dB at 15° elevation angle. Another increased value is seen at 45° horizontal angle and elevation of 0° and 15°.

Results for the Brüel and Kjær 4100-D manikin in 0.3÷1 kHz frequency range (Fig. 2, lower left panel) show similar pattern to that measured for subjects, however, in more schematic way. In the L condition, the RMSD is very small, well below 1 dB. In the S condition, slight (still below 1 dB) increase of the RMSD at horizontal angles of 45° and 135° is seen, thus at angles similar to that either for WUT data or LISTEN database. Minimal variability in the L condition and slightly larger RMSD values in the S condition for frequency range 0.3÷1 kHz is likely an effect of head and possibly pinna shadowing as the maximum variability occurs at horizontal angle of 135°.

In 1÷5 kHz frequency range (Fig. 2, middle column), the RMSD values are consistently larger than ones in low frequency range for all sets of data in all conditions. For the WUT data, the variability in the L condition is amounting to about 2 dB independently from the elevation angle. Variability in the S condition is the largest for 0° elevation, reaching 6 dB for 60° horizontally. This RMSD values gradually decrease with elevation increased to 15°, 30°, and then 45° down to RMSD of about 2÷3 dB.

For the LISTEN database in the frequency range of 1÷5 kHz (Fig. 2, middle panel), the RMSD values amount to 4 dB in the L condition and 7 dB in the S condition, larger values than in case of the WUT data. Directional pattern in the S condition with the largest RMSD values at horizontal angles of 60°÷90° is similar to that seen for the WUT data. There is also a similar decrease in RMSD values with elevation angle increased to 45°.

For Brüel and Kjær 4100-D manikin in frequency range of 1÷5 kHz (Fig.2, lower middle panel), the RMSD is below 2 dB in the L condition what shows negligible difference in direct exposure of left and right ears to the sound source. In the S condition, there is sharp RMSD increase to 8 dB for horizontal angle between 60° and 100° especially large at 0° elevation angle. This somehow follows enlargement of the RMSD in WUT data and LISTEN database for similar horizontal angle. Considering hard surface of head and torso (lack of wig or a cloth) and symmetric manikin shape with respect to the median plane, this large RMSD values in the S condition are hard to explain.

In summary, in the 1÷5 kHz frequency range, the RMSD values are still small with limited variability with angle in the L condition. However, in the S condition, moderate effect of head shadowing which decreases with elevation angle is observed. This effect is likely caused by a change (shortening) of the path length around the skull to the shadowed ear.

At frequency band of 5÷10 kHz (Fig. 2, right column), as expected, in both the L and S conditions, variability of RMSD values is larger than it may be observed for frequencies below 5 kHz. This is related to the larger effect of differences in left and right pinnae shapes and among people in this high frequency range. For the WUT data (Fig. 2, upper right panel) in the L condition and 0° elevation angle, the minimum RMSD of 6 dB is seen for 90° horizontal angle. The RMSD value increases to about 8 dB for frontal and backward sound source positions. The RMSD visibly decreases for 45° elevation angle. In the S condition, the RMSD is similar to that in the L condition, except for larger values (6-8 dB) than in the L condition at 90° horizontal angle. It makes the RMSD angular pattern more evenly shaped regardless of the horizontal angle. The RMSD gradually decreases by about 2 dB for elevation angle increased to 45°.

In frequency range of 5÷10 kHz, the pattern of RMSD values in the L and S conditions seen for the LISTEN database and WUT data are quite similar. Directional RMSD pattern for the LISTEN database (Fig. 2, middle right panel) is more regular than that of WUT data, with RMSD values in the S condition at lateral position of the sound source (90° horizontally) also reaching 8 dB. It is smaller than for WUT data, not exceeding 6 dB, at horizontal angle of 0° and 180°. The largest difference of the LISTEN database as compared with the WUT data is related to the elevation angle between 0° and 45° where change in the RMSD is smaller than that seen in the WUT data.

For Brüel and Kjær 4100-D manikin the RMSD values with horizontal and elevation angles above 5 kHz create pattern somewhat similar to that for 1÷5 kHz frequency range (Fig. 2, lower left and middle panels). In the L condition, the RMSD is less than 3 dB at 0° horizontally, and drops to 1 dB with the increase of the elevation of sound source position. In the S condition, lateral (90° horizontally) increase in RMSD value is the largest and exceeds 10 dB. Most likely, in this high frequency range, the difference in shapes of the latex manikin earmolds causes such large and specific difference in left and right sound source positions.

Among the three considered frequency ranges, the largest RMSD values both in the L and S conditions occur for the 5÷10 kHz frequency range. This must be a result of small asymmetries in left and right pinnae shapes and not a complete symmetry of head shape and ear positions, which impose the strongest effect in the highest considered frequency range. In general, regardless of differences possibly resulting from large number of subjects, general features seen for the LISTEN database are consistent with results obtained within WUT data.

Data in Fig. 3 show the RMSD values in -45°÷0° elevation angles. The differences in the RMSD patterns as compared to the 0°÷45° elevation angles in Fig. 2 are very small. In general, the elevation angles from -45° to +45° may be treated as the most natural range angles representing our ability in listening to the sound sources positioned on broadly understood horizontal plane, with ears position on the head that act as a two-microphone matrix favoring horizontal surface and front-back directions.

The major differences seen in data presented in Fig. 3 as compared to Fig. 2 are that both for WUT data and LISTEN database smaller RMSD values are observed below 1 kHz in the S condition, and larger increase in the RMSD values at horizontal angle of 45° than 135° (compare left upper and middle panels in Figs. 2 and 3). In 1÷5 and 5÷10-kHz frequency ranges smaller change in the RMSD values is seen for elevation angle decreased to -45° than increased to +45°.

For the Brüel and Kjær 4100-D manikin the decrease in elevation below 0° provides decrease in the RMSD in the S condition with largest values remaining at 90° horizontally.

Data in Fig. 4, refer to high elevation angles from 45° to 90°. The 90° elevation refers to the sound source positioned directly above the head. Therefore, differences in the RMSD with horizontal angle, if any, are rather related to the symmetry of the measurement system (i.e. head position) with minimal effect of the head shape as the obstacle in the sound field. It has also to be noted that in the case of the LISTEN database, the HRTFs at 90° elevation was taken with a single measurement (no rotation of the subject). For this reason, the RMSD is represented by the circle in the second row of panels in Fig. 4.

In all cases in Fig. 4, the increase in elevation angle from 45° to 90° decreases the RMSD from some large value at 45° to residual value at 90°, which in most conditions assumes 1 to 2 dB for subjects (WUT and LISTEN) and 0,6 to 1 dB for the Brüel and Kjær 4100-D manikin. In most conditions, the RMSD at 45° elevation is the largest (45° elevation is marked differently by dotted and solid lines respectively in Figs. 2 and 4). Typically, either in L in or S condition, an increase in elevation angle causes greater symmetry of the RMSD values with the horizontal angle. For the manikin (lower panels in Fig. 4), the RMSD values at high elevation angles of 45°÷90° are apparently smaller than that for subjects. In the latter case, it is likely related to the increased HRTF measurement error due to limited control of the measurement geometry related to possible uncontrolled subjects' movements.

VI. DISCUSSION

Several factors are seen in data presented in Figs. 2-4. Firstly, the RMSD measure assumes increasing values as frequency increases from the range below 1 kHz (left panels) to frequencies above 1 or 5 kHz (middle and right panels). Secondly, there is certain variability of relatively large RMSD values for elevation angles up to 45° with further decrease at elevation angles changing from 45° to 90°. Thirdly, in many instances, the polar pattern of the RMSD shows large values for lateral sound source positions close to the horizontal angle of 90° in the S condition which is not so pronounced in the L condition. Finally, the results are generally similar for both groups of subjects, i.e. WUT data and LISTEN database.

The RMSD values are different and for most angles smaller for the Brüel and Kjær 4100-D acoustic manikin than for subjects. This result is not surprising considering the rigid surface and absolute stillness of the artificial test fixture during measurements leaving possible eccentricity in its position as the only source of the possible measurement error. Regardless of overall small RMSD values for manikin, there is a substantial increase in the RMSD in the S condition at horizontal angle of 90°, reaching or exceeding values recorded for subjects. This confirms that in the S condition at this lateral angle there are some substantial differences in how the left and right ear are shadowed by the head as an obstacle in the acoustic field. This effect may be due to complex addition of wave diffracted around the smooth manikin's head, stronger than for diffraction around a subject's head.

For proper interpretation of the RMSD measure it is necessary to consider which factors create large RMSD values. As seen in Eq. (1) the RMSD is the brief measure of the similarity of the left ear and right ear amplitude HRTFs averaged over predefined set of frequency points and, if desired, over a number of measured subjects. For a single measured object (subject or manikin), the RMSD would approach zero in case of identical amplitudes recorded for the left and right HRTFs. The sources of differences between the left and right HRTFs are twofold – they come either from the amplitude differences or shifts in the frequency. In simple case, proportionality between the left and right HRTFs by factor k would create the RMSD = k (expressed in decibels in Figs. 2-4). However, the stronger factor creating the large RMSD values comes from slight but significant differences of the HRTFs in frequency. There are deep notches in the amplitude HRTFs in the mid and high frequency ranges which are due to slight differences in reflection patterns resulting from differences in geometry of pinnae, especially conches, of the left and right ears [1-4]. These notches, an important amplitude-frequency features essential for determining the direction of incoming sound, and may be as deep as 20 dB. Their position in frequency may be slightly shifted (by a few tens of hertz) between left and right ear. Misaligning of such notches in frequency spectrum causes large increase in the RMSD measure. Therefore, the large RMSD values is also a measure of the presence of between-ear frequency response differences significant for localization ability. As strong notches occur in frequency range above 1 and 5 kHz, the RMSD measure assumes larger values there than at frequencies below 1 kHz, as seen in Figs. 2-4.

Errors in HRTF measurements is the next issue to mention. Most difficult factor to control are unintentional subject movements, especially movements of the head, during measurement session. This is obviously avoided in the measurements with the use of acoustic manikin. Thus, assuming almost ideal median symmetry of a manikin as

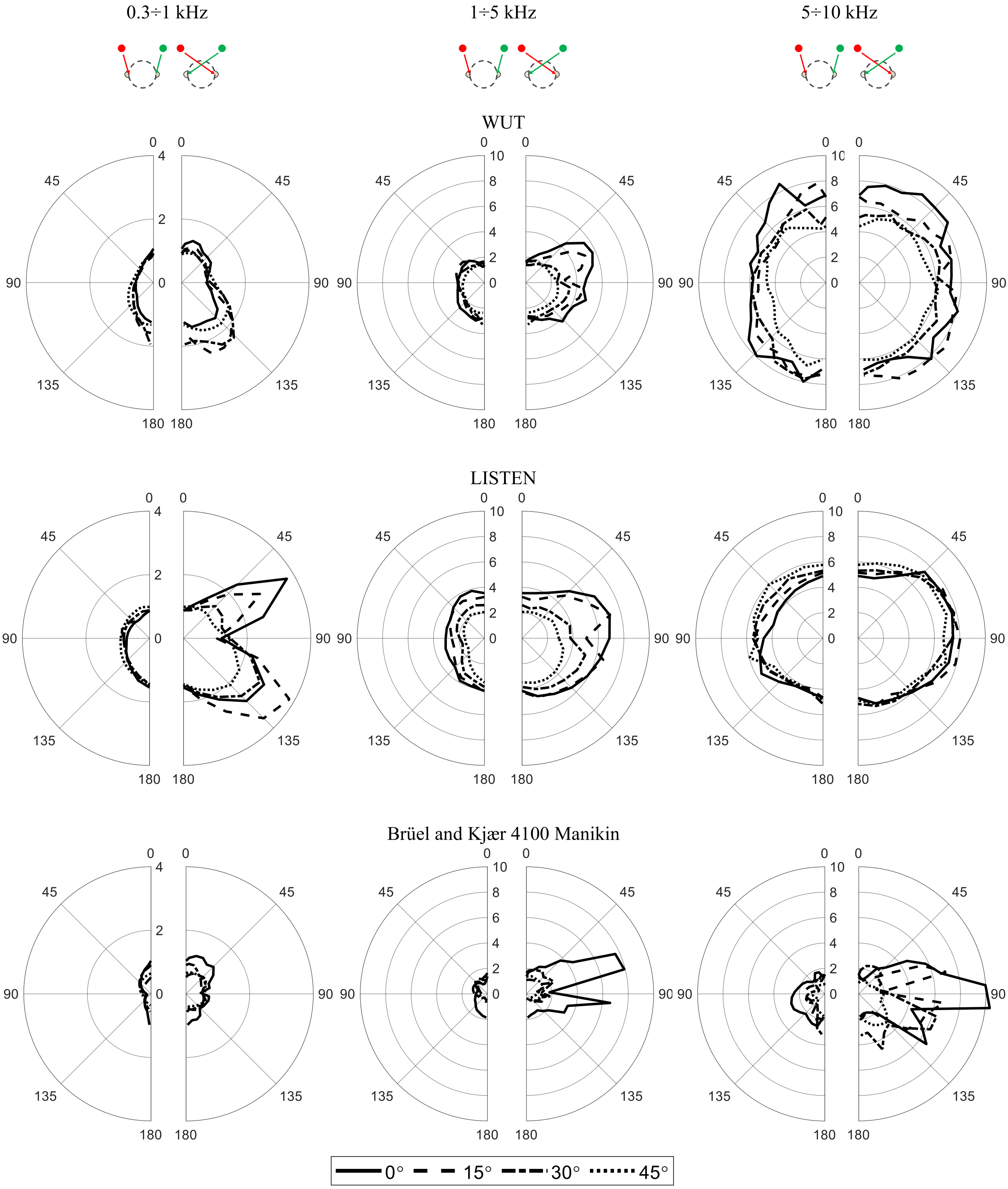

Fig.2. The RMSD of left-right HRTFs at elevation angles 0° to 45° in L and S conditions for WUT data (upper row), LISTEN database (middle row) and acoustic manikin (lower row). Data for 0°, 15°, 30°, and 45° elevation angles are represented by solid, dashed, dash-dot and dotted lines, respectively. Left semipolar plots refer to the L condition with both ears exposed to sound source. Right semipolar plots refer to the S condition with sound source shadowed by the head.

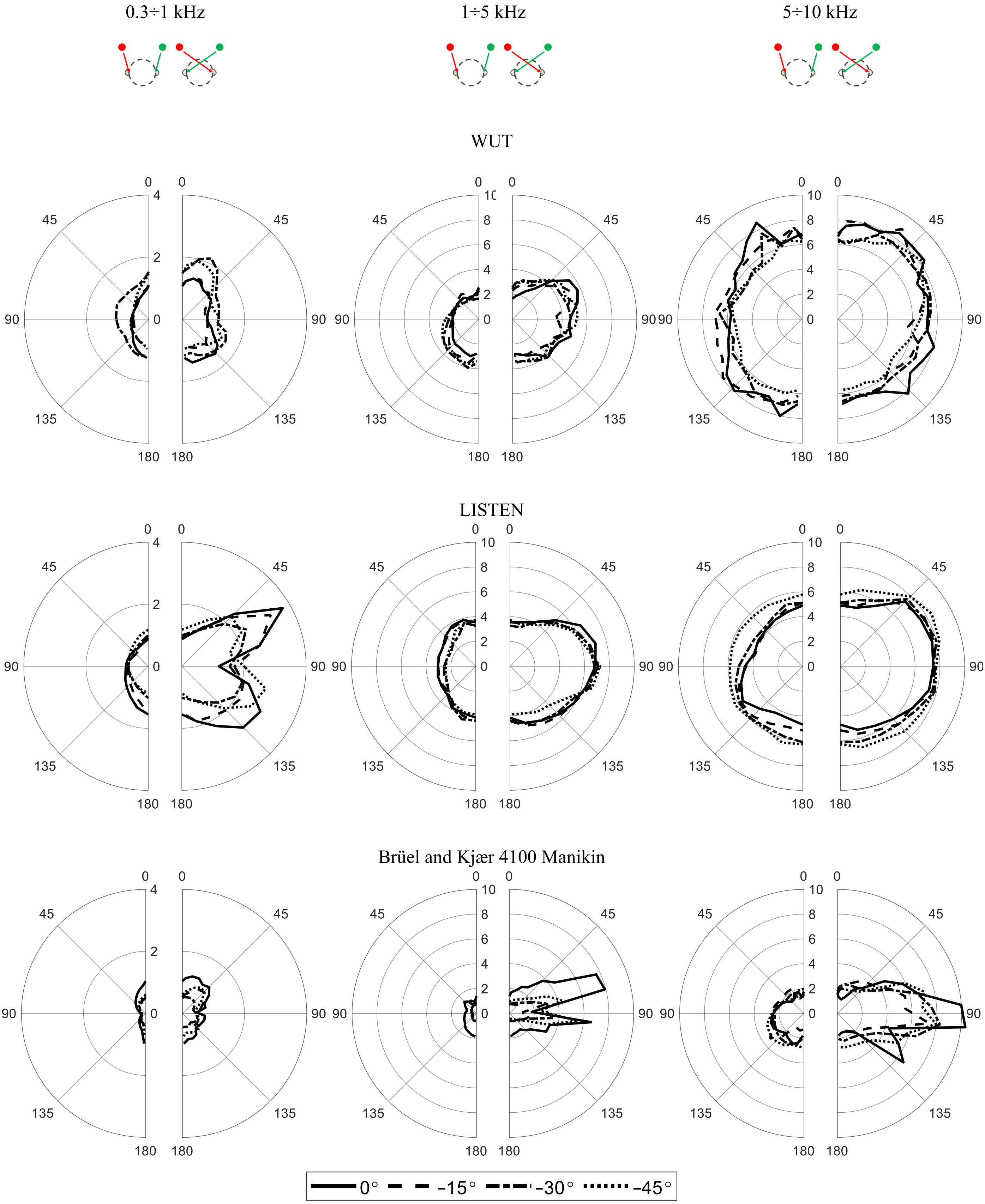

Fig.3. The RMSD of left-right HRTFs at elevation angles -45° to 0° in L and S conditions for WUT data (upper row), LISTEN database (middle row) and acoustic manikin (lower row). Data for 0°, -15°, -30°, and -45° elevation angles are represented by solid, dashed, dash-dot and dotted lines, respectively. Left semipolar plots refer to the L condition with both ears exposed to sound source. Right semipolar plots refer to the S condition with sound source shadowed by the head.

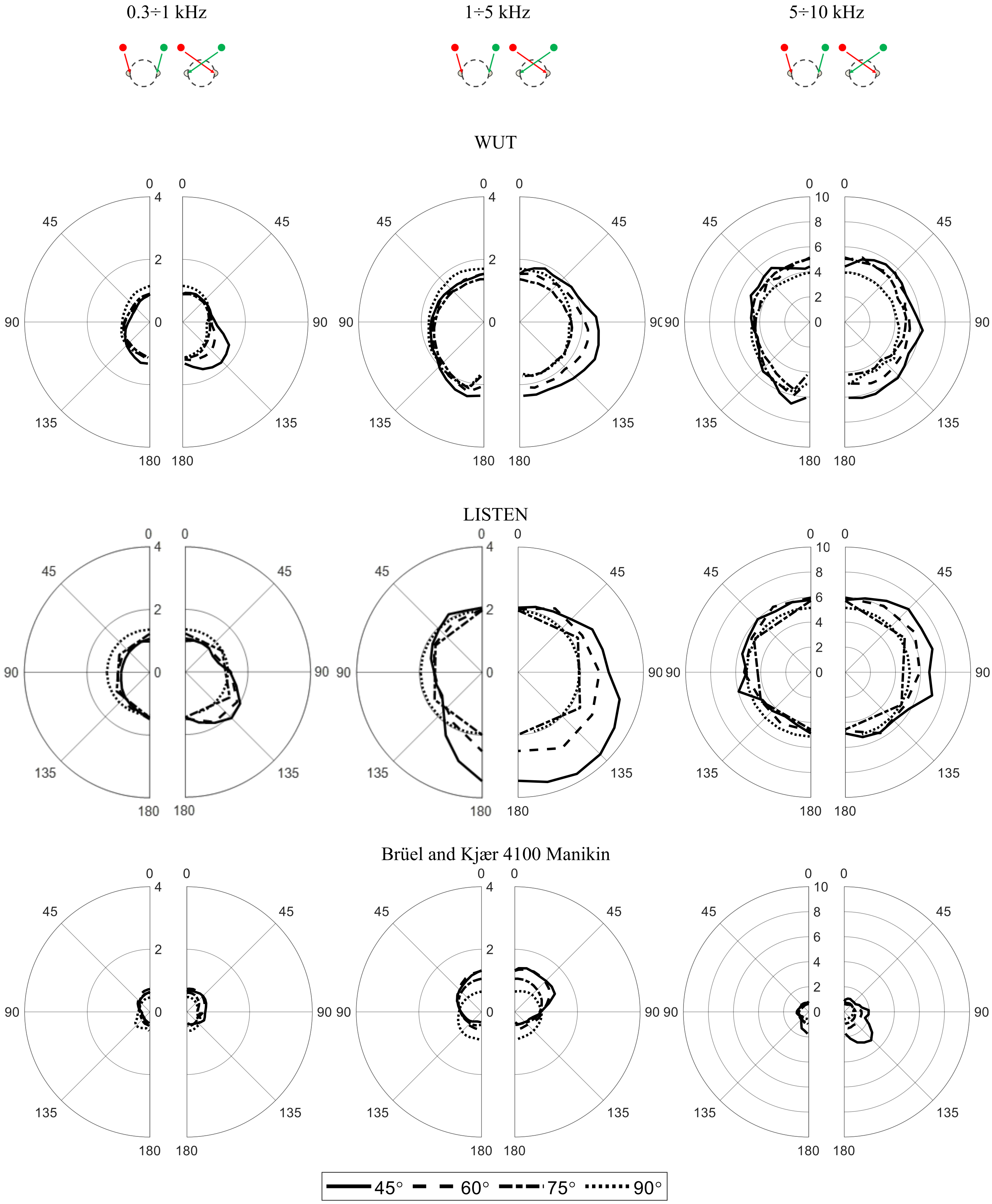

Fig. 4. The RMSD of left-right HRTFs at elevation angles 45° to 90° in L and S conditions for WUT data (upper row), LISTEN database (middle row) and acoustic manikin (lower row). Data for 45°, 60°, 75°, and 90° elevation angles are represented by solid, dashed, dash-dot and dotted lines, respectively. Left semipolar plots refer to the L condition with both ears exposed to sound source. Right semipolar plots refer to the S condition with sound source shadowed by the head.

compared to human subject and manikin's still position during HRTF measurement, small RMSD values should be expected and these values are a kind of a measure of all additional sources of measurement error. This is the case in our data in which, for instance, in the L condition the RMSD for subjects is in the range of 6-8 dB whereas for the Brüel and Kjær 4100-D manikin is smaller than 2 dB.

CONCLUSIONS

In this study, the simple RMSD measure was presented to assess the left- right- ear HRTF variability. The results for WUT data measured in our laboratory with the participation of human subjects, data taken from publicly available LISTEN database of human HRTFs, and measured with the use of the Brüel and Kjær 4100-D manikin showed that:

1. The RMSD as a measure of the left- right-ear HRTF differences assumes noteworthy values for a frequency range above 5 kHz, or at least above 1 kHz. This is an effect of the presence of more complex HRTF amplitude changes with frequency resulting from slight differences in anatomical structures related to head and pinnae in the acoustic field.

2. The asymmetry for the sources located within some range below the axial plane at 0° elevation angle remains in the same order of magnitude as for the sources above the 0° elevation angle (±45°).

3. The HRTFs may be considered left-right symmetrical in the lower frequency band of 0.3÷1 kHz.

4. The asymmetry decreases for the sound sources located at higher elevation angles, especially for elevation angles larger than 45°. This is likely caused by smaller than in the 0° plane effect of pinnae shape in the acoustic field (pinnae are directed to increase differences between front-back sound source positions).

5. Typically, focus is on pinnae shapes considered as a pair of directional sound reflectors supporting spatial hearing. The results in the S condition, for which pattern of the RMSD values is uneven with horizontal angle and different from L condition was obtained, ensure that the HRTF of the shadowed ear is equally important in supporting the directional hearing.

6. Similarity of the RMSD values for WUT data and LISTEN database, regardless of the different number of subjects, ensures the validity of measurements in both cases.

7. Data obtained with the use of the Brüel and Kjær 4100-D manikin should be considered as taken for an idealized individual subject. They likely show the minimal available RMSD values. Results with the use of the manikin cannot be considered as fully representative for any measurement taken with the participation of a human subject or to represent mean spectral RMSD values of the human subjects' population.

Conceivably the results of this work may be useful for a brief assessment of the left-right HRTF symmetry as a criterion for individualization and personalization algorithms and models of the HRTF and in the assessment of the localization errors unfortunately common in auralizations done with the use of HRTFs.

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