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Effect of Individualized Head-Related Transfer Functions on Distance Perception in Virtual Reproduction for a Nearby Sound Source

Guangzheng YU*, Liliang WANG

Acoustic Lab, School of Physics and Optoelectronics
South China University of Technology
No. 381 Wushan Rd., Guangzhou, 510641, P. R. China
*Corresponding Author e-mail: scgzyu@scut.edu.cn

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The head-related transfer function (HRTF) is dependent on the position of the sound source (both direction and distance) and is also affected by individual anatomical parameters. Individualized HRTFs have been shown to affect the perception of sound direction, but have not been considered in distance perception. This work aims to discover, by means of psychoacoustic experiments for a virtual reproduction system through a pair of in-ear headphones, the effect of individualized HRTF on auditory distance perception for a nearby sound source. The individualized HRTFs of six subjects and the non-individualized HRTFs of a mannequin at seven distances between 0.2 and 1.0 m and five lateral azimuths between 45° and 135° in the horizontal plane were processed with white noise to generate binaural signals. Further, the individualized and non-individualized HRTFs were used in the auditory distance perception experiments. Results of distance perception show that the variance of distance perception results among subjects is significant, the reason could be the stimuli are lack of dynamic cue and early reflections, or the auditory difference of distance perception among subjects. However, via the analyses of mean slope of perceptual distance and correlation between the perceptual and real distance, we find that the individualized HRTF cue has insignificant influence on distance perception.

Keywords: head-related transfer function; auditory distance perception; individual cue; virtual sound reproduction.

1. Introduction

Sound source localization by humans, which includes both directional and distance aspects, plays an important role in daily life. In general, the human auditory system is not as good at estimating sound source distance as it is at estimating sound source direction (Xie, 2013). Perception of distance is crucially important because it helps us improve speech intelligibility when both noise and signal sound source are separated in space, and to avoid obstacles in crowded traffic environments, etc.

Distance localization cues include the variation in sound intensity with the distance of the sound source, the head effect (reflection or shadow effect) and binaural cues for nearby sound sources, as well as dynamic cues caused by head movements, etc. (Zahorik *et al.*, 2005). Intensity, as a relative distance cue, has most often been considered as the primary cue and, as a consequence, has been frequently researched (Ashmead *et al.*, 1990; Zahorik, Wightman, 2001b; Spagnol *et al.*, 2017). Mershon *et al.* (1989) reported that the perceived auditory distance increased with the increment of reverberation time. In the proximal region, the interaural level difference (ILD) increases as the sound source approaches the head, especially when the sound source is near the interaural axis, which provides a strong binaural cue to improve auditory distance localization (Brungart, Rabinowitz, 1999). For sounds presented via headphones, distance perception has been linked with sound externalization and internalization (Hartmann, Wittenberg, 1996) where binaural cues are important even in the absence of the intensity as a cue (Baumgartner *et al.*, 2017). In addition, some non-acoustic cues, such as vision and familiarity with the sound, influence distance perception (Kolarik *et al.*, 2016). Among the factors mentioned above, the head effect and binaural cues for nearby sound source distance perception can be assessed using the virtual reproduction platform based on signal processing that uses head-related transfer functions (HRTFs).

An HRTF describes the acoustic transmission from a point sound source to a human subject's eardrums or ear canals in the free-field, and is a useful method for creating a virtual auditory environment for training or navigation (Bălan *et al.*, 2015; Bujacz, Strumiłło, 2016; Xie, 2013). When the distance of the source from the center of the head is greater than 1.0 m, HRTFs are approximately independent of distance and are termed far-field HRTFs. When the distance is less than 1.0 m, HRTFs vary with distance and are termed near-field HRTFs. Brungart and Rabinowitz (1999) reported that the average low-frequency gain of near-field HRTFs increases more than that of the high-frequency gain as the distance of the sound source decreases. Otani *et al.* (2009) investigated the spectral shape of near-field HRTFs numerically and reported that the central frequency, depths and widths of spectral peaks and notches vary significantly with distance. Spagnol (2015), by using KEMAR's HRTFs, pointed out that the pinna spectral patterns are dependent of distance when the sound sources are close to the interaural axis. These peaks and notches are contributed mainly by pinna, and thus the individual factors should also be considered when the distance dependence of near-field HRTFs is investigated. As defined, HRTF is an individualized physical quantity. Thus, the individual cue of HRTFs could affect the distance perception of the sound source; however, this has not been verified in any previous studies.

In fact, individualized HRTFs are vital to virtual reproduction systems and are sometimes required in order to create a better virtual sound environment (Väljamäe *et al.*, 2004). Some researchers have found that individualized HRTFs help subjects locate the sound source direction better than non-individualized HRTFs (Møller *et al.*, 1996). However, previous studies of individualized HRTFs have focused on far-field HRTFs rather than the distance dependence of near-field HRTFs because the individualized near-field HRTF database was not then available (Yu *et al.*, 2010). Recently, the individualized near-field HRTF database has been established in our laboratory by using a carefully designed measurement system. The database includes 56 Chinese human subjects, seven source distances from 0.2 m to 1.0 m, and 685 directions at each distance for each subject (Yu *et al.*, 2018). Therefore, in our current work, our main aim is to examine the effect of individual cues on near-field HRTFs and the auditory distance perception of nearby sound sources by means of psychoacoustic experiments via a virtual reproduction platform.

2. Individual differences of near-field HRTFs

Theoretically, HRTFs are defined in three dimensions and can be described by the elevation (ϕ), azimuth (θ) and distance (r) of the sound source (Xie, 2013). In comparison with other elevations, the binaural cue in the horizontal plane (where $\phi = 0°$) is prominent. Therefore, in order to simplify the problem, we choose only near-field HRTFs at several azimuths in the horizontal plane. The relationship between the position of the sound source and a subject is shown in Fig. 1, where $\theta = 0°$ (or $90°$) corresponds to the front (or right), respectively.

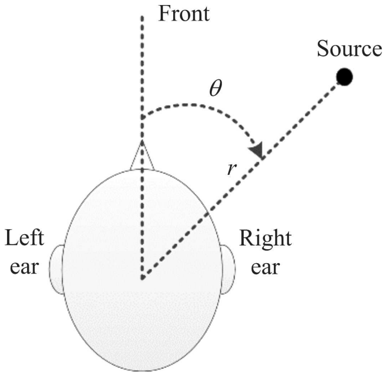

Fig. 1. Schematic diagram of azimuth and distance of near-field HRTFs in the horizontal plane.

Six participants denoted by S1, S2, S3, S4, S5 and S6 in the following content, respectively, volunteered as subjects in the study, whose HRTFs were in the near-field HRTF database established in our laboratory (Yu *et al.*, 2010; 2018), including KEMAR (the Knowles Electronic Manikin for Acoustic Research). Figure 2 shows the HRTF spectra of subject S1 with sound sources at 7 distances in the direction of directly right ($\theta = 90°$) in the horizontal plane. Results show that the near-field ipsilateral HRTF spectral magnitude decreased as the sound source distance increased at low frequencies, while the contralateral HRTF mag-

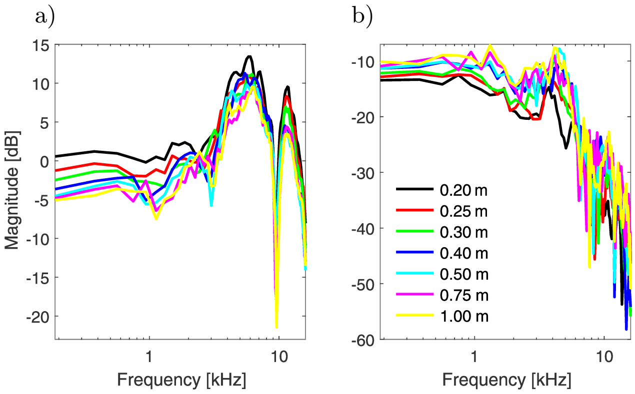

Fig. 2. The HRTF spectra of subject S1 with seven sources from 0.20 m to 1.00 m located at azimuth of 90° in the horizontal plane: a) ipsilateral, b) contralateral.

nitude increased, which is consistent with results of Brungart and Rabinowitz's study (1999). In fact, the ILD variations with distance at low frequencies are considered as an important cue of near-field distance perception (Brungart *et al.*, 1999), which is directly affected by the magnitude of the HRTF spectra. Therefore, the individual differences in ILDs at low frequencies among the subjects are worthy of further study.

2.1. Individualized ILDs

Figure 3 shows the average ILDs of the six subjects and of KEMAR in two frequency bands, below 0.5 kHz (corresponding to the head effect) and from 0.5 to 3 kHz (corresponding to the effects of the head and torso), with sound source distances of 0.25 m, 0.50 m, and 1.00 m. Though there are some slight differences between the ILD amplitudes for each subject (e.g., both the ILDs of subject S6 and their variation with distance are smaller than those of the other subjects), the trends in the variation of ILD with distance for each subject are similar, namely, the average ILD decreases significantly as the source distance increases, which is in accordance with the findings of Brungart and Rabinowitz's (1999) and Duda and Martens's (1998).

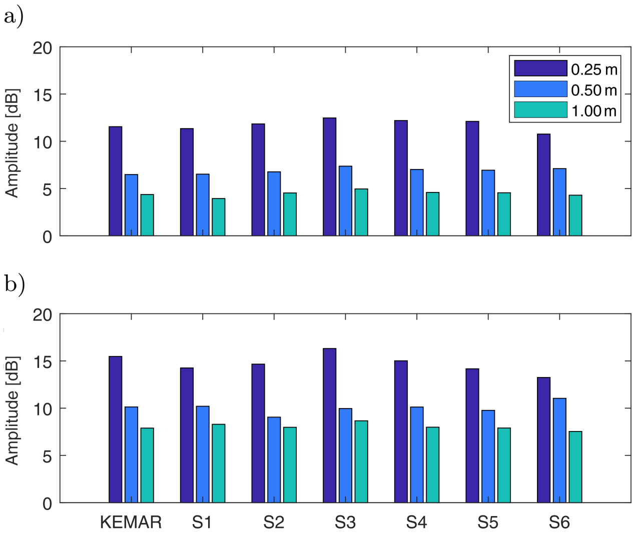

Fig. 3. Average ILD of six subjects (denoted by S1, S2, ..., S6) and of KEMAR in two frequency bands, below 0.5 kHz (a) and from 0.5 to 3 kHz (b), for distances of 0.25 m, 0.50 m, and 1.00 m.

2.2. Individualized HRTF notch frequencies

Otani *et al.* (2009) discovered that the spectral shapes of near-field HRTFs vary with the distance of the source. However, the diversity of the individualized spectral shapes and its effect on distance perception have not been analyzed and verified. Figure 4 shows the ipsilateral HRTF spectra of 6 subjects (denoted by S1, S2, ..., S6) and KEMAR in high frequencies, with the horizontal-plane sound sources located at 0.20 m (the nearest) and 1.00 m (the furthest) in directly right (θ = 90°). Results show that the spectral curves at high frequencies vary with distance, but the variance among subjects was more significant, which appears in the widths, depths, and center frequencies of the peaks and notches.

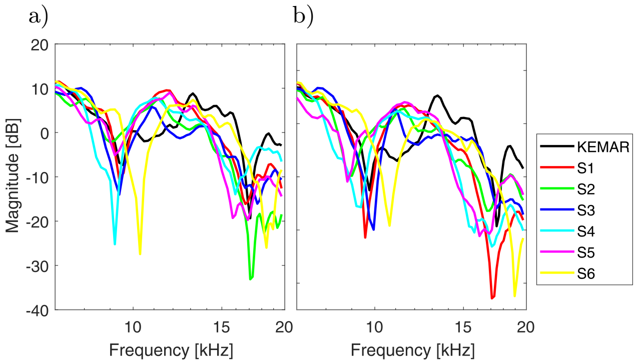

Fig. 4. The ipsilateral HRTF spectra of 6 subjects (denoted by S1, S2, ..., S6) and KEMAR in high frequencies, with the horizontal-plane sound sources located at: a) 0.20 m (the nearest), and b) 1.00 m (the furthest) in directly right (θ = 90°).

The notch frequency is usually considered as the representative feature of the high-frequency characteristics of HRTFs (Moore, 2003). Therefore, in this section, we analyze the variation in notch frequencies with distance, which differed from subject to subject. Figure 5 presents the notch frequencies of HRTFs between 6 and 11 kHz for sound source azimuths of 45° and 90° in the horizontal plane. The results show that, for each subject, the notch frequency variation tendency is not obvious when the sound source distance ranges from 0.20 m to 1.00 m in the same direction, which pales into insignificance when compared with the difference among subjects. At the same source distance, the notch frequencies varied significantly from subject to subject and from azimuth to azimuth, and the difference could be more than 1 kHz, which is consistent

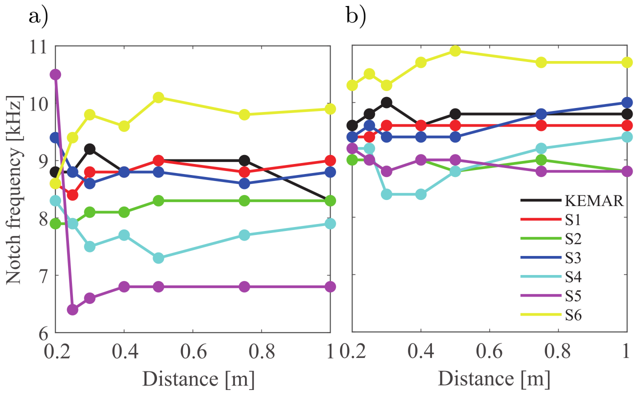

Fig. 5. Notch frequencies (kHz) of ipsilateral HRTFs at high frequencies for sound source azimuths of 45° (a), and 90° (b) in the horizontal plane.

with the notch frequency deviation 1.05 kHz of CIPIC database (Algazi *et al.*, 2001).

These differences are contributed mainly by the different anatomical parameters of the subjects and give rise to the personalized features of HRTFs. The HRTFs in other azimuths gave similar results, which accords with the findings of Møller and Sørensen (1995) and Riederer (1998). Even so, the spectral difference (especially the notches at high frequencies) between various subjects needs to be validated in auditory distance experiments.

3. Distance perception experiment

As results mentioned in Sec. 2, the low-frequency ILD increases as the distance decreases, but the ILD variance differs slightly among subjects. Otherwise, the notch frequency variance caused by distance is insignificant when compared with the difference among subjects. Anyway, both the individual difference and distance dependence actually appear in near-field HRTFs. Therefore, the comprehensive effect of individualized near-field HRTFs on distance perception is worthy of investigating via a distance localization experiment. Six volunteers mentioned before, including four males and two females aged between 25 and 39, completed this experiment as listeners, including five students and one teacher in the acoustic field. They all had normal hearing and all had experience of psychoacoustic experiments.

The individualized HRTFs of the six participants and the non-individualized HRTFs of a KEMAR have been measured in our laboratory (Yu *et al.*, 2010; 2018). In the psychoacoustic experiments, non-individualized HRTFs of the KEMAR were used for all listeners as the control group. More specifically, all the subjects shared the same non-individualized HRTF. The representation of the HRTF in the time domain is head-related impulse response (HRIR), which was applied directly to the signal processing of stimulus generation (see Subsec. 3.1). This experiment was performed in a listening room of our laboratory, in compliance with international electronic standards (IEC), with background noise below 30 dBA.

3.1. Stimulus generation

A mono signal of white noise with a full range of frequencies was convolved, respectively, with the HRIRs of the six subjects and of a KEMAR to generate the stimulus signals of virtual sound sources at seven distances (r = 0.2, 0.25, 0.3, 0.4, 0.5, 0.75, and 1.0 m) and five azimuths (θ = 45°, 60°, 90°, 120° and 135°). The sound source azimuths coming from 0° and 180° were considered in a pre-experiment. At azimuths of 0° or 180°, however, it was difficult to distinguish the sound sources at various distances, and some listeners reported either in-head localization or reversal error (Wightman, 1989). Therefore, the sound sources close to the median plane were not involved in the following formal experiments. The stimulus convolved from each subject's individualized HRIRs and of the KEMAR's non-individualized HRIRs were used as the compare and control groups, respectively.

In order to make the individual cue more effective during virtual reproduction for nearby sources, all other distance localization cues were excluded, such as the dynamic cue caused by head tracking and the reflections in the room. In the aforementioned signal convolution for virtual reproduction, the dynamic cue and the reflections were not contained. For the sound intensity (or loudness) cue, before convolution with white noise, the gain coefficients $\{a_i\}$ (i = 1, 2, 3, 4, 5, 6 for the six subjects, respectively) were applied to keep the sound intensity of the subjects' individualized HRTFs consistent with the non-individualized HRTFs of KEMAR. The sound pressure $P_0(r_0, \theta_0)$ of KEMAR was set as the reference sound pressure. The psychoacoustic experiments were divided into five groups according to the azimuths. Therefore, for each listener, the gain coefficient a_i for each azimuth was obtained by calculating the sound energy ratio of the individualized to non-individualized HRTFs (the reference value) at a distance of 0.2 m.

Stimulus signals were presented to listeners through in-ear headphones (type Etymotic Research ER2), which avoided the procedure of headphone equalization of binaural virtual reproduction (Kulkarni, Colburn, 1998).

3.2. Procedures

As mentioned in Subsec. 3.1, the psychoacoustic experiments were divided into five groups on account of the five azimuths of the stimulus signals. For each participant, the sequence of the five groups was random. Before each group started, subjects were informed about the direction from which the stimulus would be presented. There were seven auditory distances in each direction. Each distance consisted of both individualized and non-individualized signals, and each signal was repeated four times so that there were $7 \times 4 \times 2$ signals in each direction that were all presented randomly and differed both from group to group and from subject to subject. A frame with scales was placed in front of each participant. The height of the frame was about the same as that of the listener's ears, who sat on a chair during the experiment. After hearing the stimulus signals, the participant made a judgment about the auditory distance and used a stick to point to a position on the frame and then an assistant recorded the scale readings. For each presentation, the participant was allowed to hear the signal not more than three times.

4. Analysis

4.1. Results of distance perception

Figure 6 shows the near-field distance perception experiment results of all of the subjects. This figure demonstrates that it is possible to distinguish between simulated sound signals at different distances in a virtual sound reproduction system within the degree range from 45° to 135°.

Figure 6 illustrates a general tendency of overestimating distance when the source is near the head or

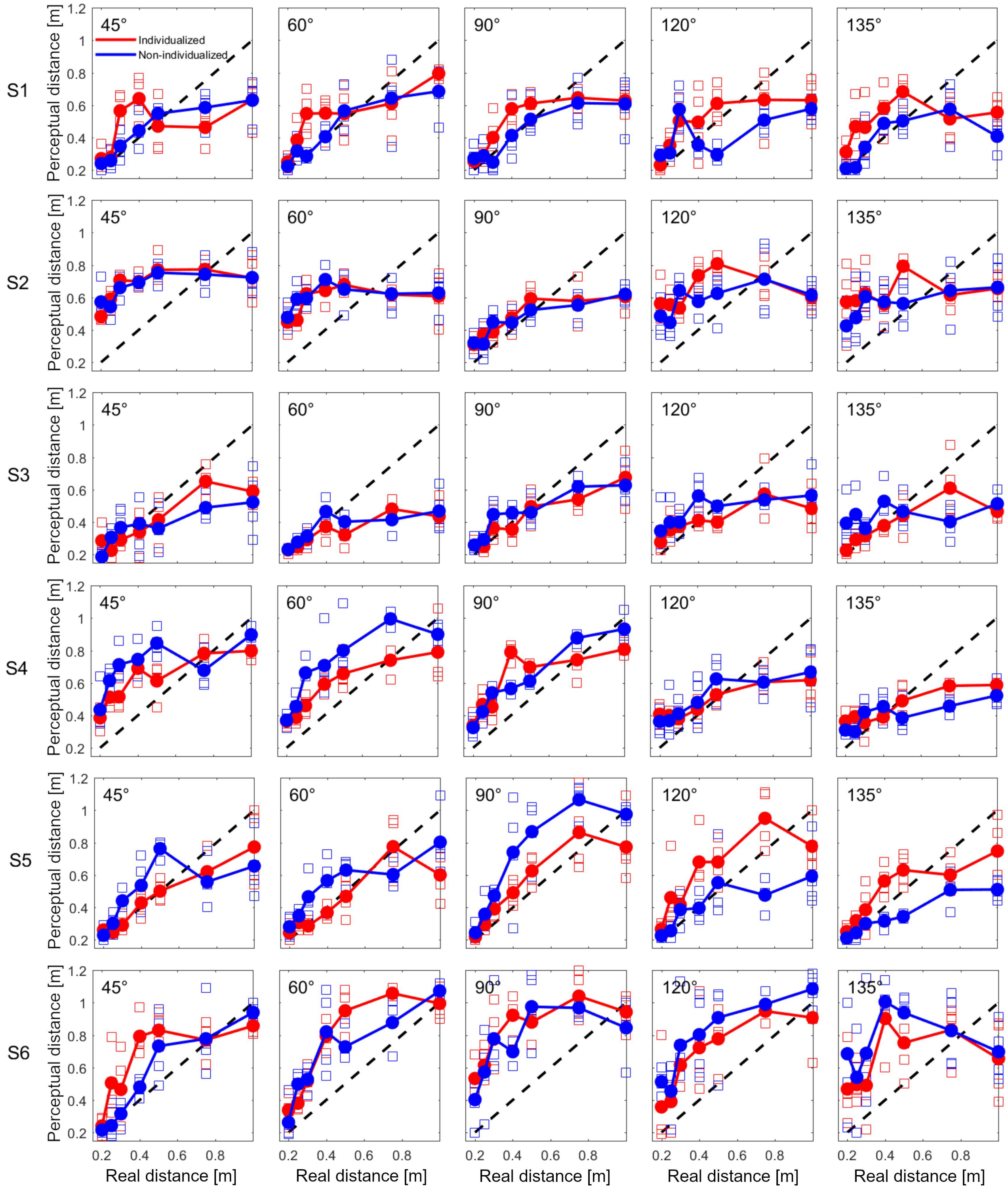

Fig. 6. The distance perception experiment results of all of the six subjects. For each subject, five panels represent five azimuths (45°, 60°, 90°, 120°, 135°). The dash line indicates correct response. The hollow square represents raw distance data while the filled circle represents the average result of raw data at the same distance.

underestimating distance when the source is far (but still in proximal region), which is similar with the study of Brungart *et al.* (1999).

As we can see, the variance of distance perception results among subjects is significant. The reason could be the stimuli are missing the dynamic cue and the early reflections, or the auditory difference of distance perception among subjects. For example, in comparison, the distance perception performance of subjects S1, S4 and S5 seems similar and matches the real distance better, the perceived distance of subjects S2, S3 is over-compressed, and the distance perception of subject S6 is over-expanded. However, this study does not focus on the variance among subjects, but focus on the effect of individualized HRTFs on the distance perception via analyzing the experiment results of 6 subjects.

4.2. Correlation between perceptual and real distance

To further investigate the difference in auditory distance perception between individualized and non-individualized simulated signals, we calculated the Pearson correlation coefficient r between the perceptual distance and the real distance for both individualized and non-individualized simulated signals, as shown in Fig. 7. It can be clearly seen that when the sound source is on the lateral and anterior side, the perceptual distance has a strong correlation with the real distance, for both individualized and non-individualized simulated signals. When the sound source is on the interaural axis, the correlation coefficient r reaches its greatest value. As the sound source approaches the posterior side, the correlation coefficient r becomes less, but still has a moderate correlation at an azimuth of 135°. When the sound sources are at the same azimuth except for the case of 90°, the correlation coefficient r between the perceptual distance and the real distance of individualized signals is slightly better than that of the non-individualized signals.

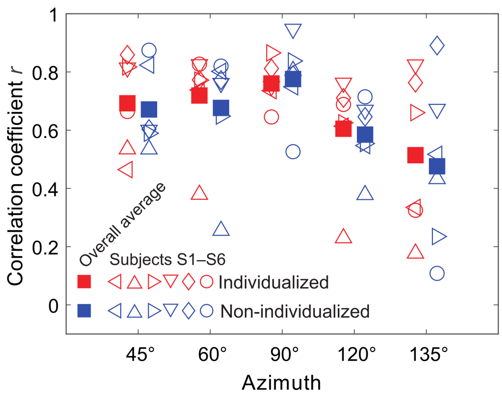

Fig. 7. Correlation coefficient r between perceptual distance and real distance given as a function of azimuth. The hollow symbols indicate different subjects, while the filled squares indicate the overall average.

A two-way, repeated-measures analysis of variance (ANOVA) with the factors of signal type (individualized vs non-individualized) and direction (45°, 60°, 90°, 120°, 135°) was performed. The main effect of direction reaches significance [$F(4,50) = 3.763$, $p = 0.009$]; both the main effect of signal type and the interaction of signal type and direction are not significant [$F(1,50) = 0.194$, $p = 0.661$ and $F(4,50) = 0.044$, $p = 0.996$]. That's to say, sound sources processed with individualized HRTFs do not contribute the accuracy of listeners' distance localization in static virtual reproduction system much, compared to that processed with non-individualized HRTFs.

4.3. Mean slope of perceptual distance

The variance of perceptual distance range among subjects was discussed before. And it could be different between individualized signals and non-individualized signals. The perceptual distance range shows the subject's ability to compress or expand the response in distances, which can be represented by the slope of the linear fit of the distance data. Figure 8 demonstrates the mean slope of the linear fit of distance data across all subjects and standard deviation. The mean slopes of perceptual curves at all directions are all smaller than 1, both for individualized and non-individualized signals, demonstrating a general tendency that listeners compress the perceptual distance in near-field static reproduction system. It demonstrates that the overall trend of the perceptual distance curves is closer to the real distances when the sound source gets close to the interaural axis ($\theta = 90°$). This is expected, as the sound source in the interaural axis provides the biggest ILD cue, and this result is similar to that reported by Kopco and Shinn-Cunningham (2011), in which judgments are relatively accurate for lateral sources. As the sound source approaches the posterior side, the slope becomes shallower, which indicates the relatively low accuracy of distance perception. The perceptual distance curves at azimuths of 120° and 135° tend to be flat when the real distance exceeds about 0.5 m.

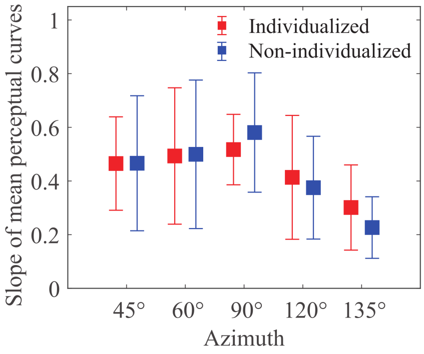

Fig. 8. The mean slope of the linear fit of distance data across all subjects and standard deviation.

The slope data was entered into a repeated measures analysis of variance with signal type (individualized and non-individualized) and direction (45°, 60°, 90°, 120°, 135°). The main effect of direction is significant [$F(4,50) = 3.393$, $p = 0.016$]; both the main effect of signal type and the interaction of signal type and direction are not significant [$F(1,50) = 0.025$, $p = 0.875$ and $F(4,50) = 0.188$, $p = 0.944$].

Though there were differences of personalization in the objective physical quantities of near-field HRTFs, the differences did not improve the reproduction effect in this virtual reproduction system based on individualized near-field HRTFs. This may have been due to the fact that the overall performance of distance perception was relatively poor, and the individual cue was not outstanding in distance perception. In addition, errors could also have been introduced by the signal processing or reproduction method (presented through headphones) in the virtual reproduction system, which resulted in differences between the simulated sound and the actual sound, to some extent, and thus could have destroyed the effect of the individualized HRTFs.

5. Conclusions

In this work, we analyzed the individual difference and distance dependence of near-field HRTFs for 6 subjects and found the possible distance localization cue. Then, we conducted a psychoacoustic experiment to investigate the effect of individualized HRTFs on distance perception in static virtual reproduction for nearby sound sources, and the procedures used and the results obtained are described. The perception of auditory distance is more accurate when the nearby sound source generated with HRTFs is on the anterior and lateral side than when it is on the posterior side (azimuth ranges from 45° to 135° horizontally). In the same direction, the perceptual distance results for both individualized and non-individualized signals are insignificantly different. In other words, individualized HRTFs have an insignificant effect on the auditory distance perception of nearby sources in the existing virtual reproduction system. The reason for this could be that distance perception itself is relatively poor via virtual reproduction for a nearby sound source, and dynamic cue and early reflection are not concerned in the study, so that the individual cue cannot be outstanding in distance perception. Future experiments are necessary to determine whether other distance localization cues influence distance perception for a nearby source.

Acknowledgments

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