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The Audibility of Spectral Detail of Head-Related Transfer Functions at High Frequency, Bosun Xie and Tingting Zhang, Acta Acustica **vol. 96** (Number 2), 2010, pp. 328-339

DOI
https://doi.org/10.3813/AAA.918282

ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 96 (2010) 328 – 339
DOI 10.3813/AAA.918282

The Audibility of Spectral Detail of Head-Related Transfer Functions at High Frequency

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Summary
A psychoacoustic experiment was conducted to evaluate the audibility of spectral detail of head-related transfer functions (HRTFs) at high frequency. The magnitude of individual HRTFs above 5 kHz was smoothed by a moving frequency window with different bandwidths and subsequently used to create virtual sound images in headphone reproduction. Results with six subjects demonstrated that the ipsilateral and contralateral HRTFs in both the horizontal and lateral planes could be smoothed only with a bandwidth of 2.0 ERB (equivalent rectangular bandwidth) and 3.5 ERB, respectively, without introducing audible artifacts. Both magnitudes of the binaural HRTFs above 5 kHz could also be smoothed with a bandwidth of 2.0 ERB for the ipsilateral ear and 3.5 ERB for the contralateral ear, respectively; whereas in the median plane, both magnitudes of the binaural HRTFs could be smoothed with a bandwidth of 2.0 ERB without introducing audible artifacts. Therefore the spectral detail of HRTFs at high frequency is inaudible. A binaural loudness model was further used to analyze the experimental results. The audibility of the smoothing artifacts of HRTFs was indicated to depend on the difference between the (monaural and binaural) loudness spectra caused by the original and smoothed HRTFs. Consequently, the result was both spatial direction and individual-dependent. In practical signal processing of the virtual auditory display, it is unnecessary to use complex signal models to represent the spectral detail in HRTF magnitude at high frequency.

PACS no. 43.66.Pn

1. Introduction

Head-related transfer functions (HRTFs) are the acoustical transfer functions from sound sources to two ears in the free field and embody the main cues for sound source localization. Therefore, they are vital to research on binaural hearing [1, 2]. One of the important applications of HRTFs is the signal processing of a virtual auditory display in which an input stimulus is filtered by a pair of HRTFs and subsequently reproduced by headphone to create spatial sound images [3, 4, 5].

For a given sound source direction, HRTFs are functions of frequency. In addition, they are individual-dependent, especially at high frequencies above 5 kHz. The complex changes in HRTFs at high frequency are due to the multipath interference of the diffracted and reflected sound waves caused by the anatomical structures, such as the head and pinnae. The spectral features of HRTFs at high frequency are important to localization [1], such that they should be accurately recreated in a virtual auditory display. Some low-frequency spectral features of HRTFs caused by head diffraction and torso reflections are also cues for elevation localization [6], but their changes are not as complex as high-frequency spectral features. Therefore, this research focused on the high-frequency spectral features of HRTFs. Conversely, due to the limited frequency resolution of the inner ear, the spectral details of HRTFs at high frequency may be inaudible. From the latter point of view, some simple signal models can be used to approximate HRTFs in a practical virtual auditory display. The approximation may lead to some mathematical errors in the resulting HRTFs of these models, but the errors may be inaudible and the signal processing is simplified. Therefore, the problem of the audibility of spectral detail of HRTFs is important to the research on binaural hearing and the application of a virtual auditory display.

Kulkarni and Colburn investigated the audibility of spectral detail of HRTFs via a psychoacoustic experiment [7]. They smoothed the HRTF magnitudes of human subjects by truncating the Fourier series of HRTF log-magnitude spectra. The log-magnitude spectra of individual HRTFs from four subjects at azimuths of 0°, 45°,135°, and 180° in the horizontal plane were smoothed and then used to create virtual sound images. The experimental results showed that the HRTFs could be signif-

Received 29 April 2009,
accepted 8 January 2010.

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icantly smoothed in frequency without affecting the perceived location of a sound. Even if the coefficients used to reconstruct HRTFs decreased from 512 to 32, subjects were unable to discriminate actual sounds presented by a loudspeaker from 'virtual' sounds presented over tubephones. Similarly, Qian and Eddins conducted a sound image localization experiment with six subjects by using the HRTFs at 72 spatial directions [8]. The results proved that applying low-pass filtering at 2 cycles/octave to the magnitude spectra of HRTFs in the spectral modulation frequency domain, which is equivalent to smoothing HRTF magnitudes in the frequency domain, did not significantly influence localization accuracy.

In the practical design of HRTF filters for a virtual auditory display, a time window is often applied to truncate the original head-related impulse responses (HRIRs, counterparts of HRTFs in the time domain), which is also equivalent to smoothing the HRTFs magnitude in the frequency domain. Certain authors investigated the effect of the HRIRs duration on the virtual free-field sound image via psychoacoustic experiments [9, 10]. The results from Senvoa *et al.* demonstrated that for an HRIR duration less than 5.12 ms, localization performance of virtual images gradually decreased compared with actual sources. Additionally, HRIRs with a duration of 1.28 ms were sufficient, if a slight loss of fidelity was tolerable. Although different authors obtained varying results, in general, HRIRs with the duration in the order of 2 ms or even less was sufficient in practice to ensure the accuracy of virtual sound image localization, which is equivalent to a 500 Hz or more coarse frequency resolution.

A uniform or linear frequency scale was used to smooth HRTFs in the works mentioned above. In order to adapt the frequency resolution of the cochlea, a nonuniform frequency scale can be used to smooth HRTFs. Carlile and Pralong proved that much of the spectral detail in the measured HRTFs disappeared after cochlear filtering, but the feature relevant to localization was remained in the excitation patterns of the cochlea [11]. Breebaart and Kohlrausch investigated the audibility of spectral detail in HRTFs and used Gammatone filterbanks with various orders to smooth the magnitude and phase of the binaural HRTFs [12]. Gammatone filters with a fourth order and 3 dB bandwidth of 1 ERB (equivalent rectangular bandwidth [13]) closely matched the frequency resolution of cochlea and processing a HRTF with lower filter orders lead to more smoothing. For three subjects and the binaural HRTFs at azimuths of 0°, 30° , and 120° in the horizontal plane, the results of psychoacoustic experiments demonstrated that smoothing the HRTF magnitude and phase, respectively, or simultaneously, by Gammatone filters with the first or higher order did not cause audible artifacts. In practical use, a moving frequency window with a bandwidth of 1/3 octave or 1 ERB was suggested to smooth binaural HRTF magnitudes [14, 15]. Frequency warping was also used to design HRTF filters to fit the frequency resolution of cochlea [15].

Previous researches demonstrated that some smoothing of the binaural HRTFs did not obviously affect localization in a virtual auditory display. Various smoothing algorithms have been applied to the practical design of HRTF filters. Due to following reasons, however, the audibility of spectral detail of HRTFs is still problematic.

1. Smoothing HRTFs may affect both localization and timbre in a virtual auditory display. The psychoacoustic experiments by Kulkarni and Colburn [7] and Qian and Eddins [8] were designed only to evaluate the performance of localization. Both localization and timbre were investigated in the experiment by Breebaart and Kohlrausch [12], but nonindividual HRTFs were used. Besides, nonindividual HRTFs with a HRTF customization procedure were used by Qian and Eddins [8]. Because hearing is more sensitive to the change of individual HRTFs as mentioned by Qian and Eddins [8] and Breebaart and Kohlrausch [12], different results might be obtained by using individual HRTFs. Moreover, the HRTFs at only four and three different azimuths in the horizontal plane were investigated, respectively, in the experiments performed by Kulkarni and Colburn [7] and Breebaart and Kohlrausch [12]. If HRTFs in additional directions were evaluated by the experiments, more general results would be obtained.
2. In previous experiments, HRTFs were smoothed within the full audio frequency range. No additional efforts were made to evaluate the HRTFs at high frequency. However, above 5 kHz where the wavelength is short and the effects of fine anatomical structures, such as pinnae, are obvious, HRTFs vary with frequency in a complicated manner. Thus, the errors caused by various approximations of HRTFs, such as application of the filter model [15], the spatial interpolation [16, 17], or the principal components analysis and reconstruction [18], are obvious at high frequency. Moreover, the measured HRTFs also exhibit greater errors at high frequency [19].
3. Both responses of the binaural HRTFs were smoothed to the same extent in previous studies, and the results of smoothing the ipsilateral and contralateral HRTFs were not compared quantitatively. Because sound waves diffract around the head of the subject before reaching the contralateral ear, multi-path interference of diffracted sound wave causes the contralateral HRTF to vary with frequency in a more complicated manner than does the ipsilateral HRTF. Thus, errors in measurement and various approximations of HRTFs are greater at the contralateral ear than that at the ipsilateral ear. Due to the shadow effect of the head, however, sound pressure at the contralateral ear is attenuated greatly at high frequency. The complex spectral detail of the contralateral HRTF at high frequency may therefore be inaudible. From this point of view, some simple models can be used to approximate the contralateral HRTF. In fact, results of psychoacoustic experiments showed that spectral cues of both ears at high frequency contribute to front-back and vertical localization. Compared with the ipsilateral ear, however, the contribution of the contralateral ear is less [20, 21]. Furthermore, Avendano

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et al. suggested that in practical signal processing, the contralateral HRTF could be modeled by a simple transformation of the ipsilateral HRTFs based on the low-pass filtering function of the spherical head model, i.e., the contralateral HRTF could be approximated by a coarse model [22].

The goal of the present study was to investigate the audibility of spectral detail of HRTFs at high frequency in the horizontal plane, the lateral plane and the median plane, respectively, particularly to compare the audibility of spectral detail of the ipsilateral and contralateral HRTFs. Magnitudes of individual HRTFs at high frequency were smoothed by a moving frequency window with different bandwidths. A psychoacoustic experiment was conducted to evaluate the audibility of smoothing artifacts (including localization and timbre). Additionally, a binaural loudness model was also used to analyze the smoothing artifacts.

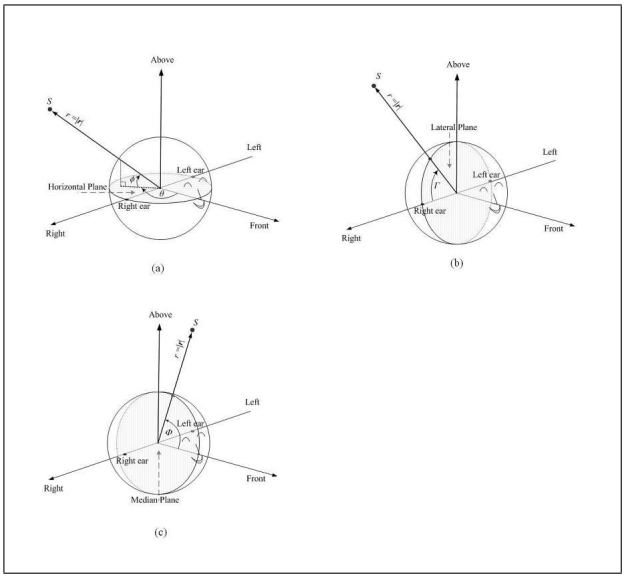


Figure 1. Spatial coordinate.

2. Experimental principles and methods

2.1. Smoothing HRTFs

As illustrated in Figure 1a, the center of the head is chosen as the origin of coordinates. Distance from a sound source to the origin is denoted by r. Sound source direction is specified by the azimuth θ from 0° to 360° and the elevation ϕ from −90° to 90°, where $\phi = 0°$ and 90° corresponding to the horizontal plane and above, respectively. In the horizontal plane, $\theta = 0°$ is the front and $\theta = 90°$ is the right.

In the frequency domain, HRTFs are defined as

$$H_L = \frac{P_L(r, \theta, \phi, f)}{P_0(r, f)}, \qquad H_R = \frac{P_R(r, \theta, \phi, f)}{P_0(r, f)}, \tag{1}$$

where f is frequency, $P_L(r, \theta, \phi, f)$ and $P_R(r, \theta, \phi, f)$ are the sound pressures at the left and right ear respectively and $P_0(r, f)$ is the sound pressure at the origin with the head absent. In the far field ($r > 1.0\,\mathrm{m}$), HRTFs are asymptotically independent of distance. The counterpart of the HRTFs in the time domain are the head- related impulse responses (HRIRs), which are the inverse Fourier transform of the HRTFs.

At a given direction and distance, HRTFs are complex-value functions of frequency, including both magnitude and phase information. To investigate the audibility of spectral detail of HRTFs, both the magnitude and phase of HRTFs should be smoothed. Previous studies proved that under most conditions, HRTFs could be represented by their minimum phase functions, cascading with a linear phase function [23, 24]. According to the theory of signal processing, the phase of a minimum phase function is uniquely determined by its log-magnitude spectrum. The linear phase function corresponds to a pure delay which is equivalent to extreme smoothing of the phase of an HRTF. Therefore, in the present study, the magnitudes of the HRTFs were smoothed, whereas the phases of the HRTFs were allowed to remain intact, i.e., being identical to that of original HRTFs.

A moving frequency window was used to smooth the magnitude of the original HRTFs. The magnitude of a smoothed HRTF at a certain frequency is determined as the root-mean square (RMS) value across the bandwidth of the window, that is

$$\left| H_S(f) \right| = \sqrt{\frac{1}{f_H - f_L} \int_{f_L}^{f_H} \left| H(f') \right|^2 \mathrm{d}f'}, \tag{2}$$

where $H(f)$ is the original HRTF, and $H_S(f)$ is the smoothed HRTF, f_H and f_L are the upper and lower bounds of the frequency window, respectively, $\Delta f = f_H - f_L$ is the bandwidth. For brevity, the parameters that denote both the position of the sound source and the left or right ear are neglected in equation (2).

Various methods can be applied to select the frequency window. The results of psychoacoustic experiments showed that the frequency resolution of cochlea could be modeled by a bank of overlapping band-pass filters. These filters can also be characterized by a bank of rectangular filters called equivalent rectangular auditory filters. The bandwidth ERB of the filters (in Hz) as a function of center frequency f (in kHz) is given by [13]:

$$\mathrm{ERB} = 24.7(4.37f + 1). \tag{3}$$

In this research, the bandwidth Δf was selected according to the equivalent rectangular auditory filters, such as values of 1.0 ERB, 1.5 ERB.

In view of the equivalent rectangular auditory filters, a new frequency scale, called ERB Number, was introduced. The relationship between ERB Number and frequency f (in kHz) is

$$\text{ERB Number} = 21.4 \log_{10}(4.37f + 1). \tag{4}$$

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2.2. The design of the experiment

The experiment was designed for HRTFs in the horizontal plane, the lateral plane, and the median plane respectively.

1. As shown in Figure 1a, in the horizontal plane ($\phi = 0°$), the direction is denoted by the azimuth θ. HRTFs from the azimuth $\theta = 30°$ to 150° and from 210° to 330° at an interval of 30° were evaluated in this experiment.
2. In the lateral plane, the azimuth θ is 90° or 270°. As shown in Figure 1b, it is convenient to introduce a new angle $-90° < \Gamma \leq 270°$ to represent the direction. Here, $\Gamma = 0°$, 90°, 180°and 270° denote directions to the right, above, left and below, respectively. HRTFs from the angle $\Gamma = -30°$ to 60° and from 120° to 210°, at an interval of 30°, were evaluated in the experiment. Because $\Gamma = 0°$ and 180° in the lateral plane are consistent with $\theta = 90°$ and 270° in the horizontal plane, respectively, the HRTFs at these two directions need not be evaluated repeatedly.
3. In the median plane, the azimuth θ is 0° or 180°. For convenience, a new angle was introduced, $-90° < \Phi \leq 270°$ to represent the direction. Here, $\Phi = 0°$, 90°, 180°and 270° denote the front, above, behind and below directions, respectively. HRTFs from $\Phi = -30°$ to 210°, at an interval of 30°, were evaluated in the experiment.

Previous research showed that smoothing HRTF magnitudes by a frequency window with a bandwidth of 1.0 ERB did not obviously affect the localization [15]. The spectral detail caused by pinnae appears above 5 kHz, and the errors in measurement and various approximation models of HRTFs are greater above 5 kHz, therefore the present experiment focused on the spectral detail of HRTFs at high frequency. Different bandwidths were chosen to smooth the magnitudes of HRTFs according to equation (2). Within the frequency range of 0.5 kHz $\leq f <$ 5 kHz, a constant bandwidth, $\Delta f = 1.0$ ERB, was chosen. Above the frequency of 5 kHz, various bandwidths were evaluated. At the frequencies below 0.5 kHz, the magnitude of the original HRTF was flat and required no smoothing. In addition, for HRTFs in the horizontal and lateral planes, the situations of smoothing the ipsilateral or contralateral HRTFs only and smoothing the both magnitudes of the binaural HRTFs were evaluated, respectively, so as to compare the audibility of spectral detail from different ears. For the HRTFs in the median plane, only smoothing of the both magnitudes of the binaural HRTFs was evaluated. Following preliminary testing, the parameters for smoothing HRTFs in different planes were chosen, as shown in Table I.

Individual HRIRs in the far field ($r = 1.5$ m) were used in the experiment [25]. Original HRIRs were measured by the blocked-ear-canal method, i.e. the binaural pressures were measured at the blocked ear canal entrances. Previous studies proved that transmission from the blocked ear canal entrance to the eardrum is one-dimensional, therefore, the directional characteristics of the sound transmission to the ear are thus best described by blocked ear canal HRTFs [26, 19]. The original HRIRs were measured at a sample frequency of 44.1 kHz with a duration of 512 samples. The frequency resolution of the original HRTFs was only 86 Hz. To improve the frequency resolution, 512 zeros were padded onto the end of the original HRIRs. The resulting frequency resolution was 43 Hz. The HRIRs were transformed to the frequency domain by a discrete time Fourier transform (DFT) and then smoothed. Subsequently, the smoothed HRTFs were transformed back to the time domain by the inverse discrete time Fourier transform (IDFT) and truncated by a time window, resulting in smoothed HRIRs with 512 samples.

A mono white noise stimulus was filtered by a pair of original or smoothed HRTFs. The resulting binaural signals were equalized by the inverse filter of individual headphone external ear transfer function [26] and then reproduced by a pair of headphones (Sennheiser HD 250 Linear II). Stimuli were presented at sound pressure level equivalent to a free-field presentation at approximately 70 dB (relative to 20 μPa rms).

Both individual HRTFs and individual head phone-external ear transfer functions used in the experiment were measured at the blocked ear canal entrance. In this case, if the resulting signals are reproduced by a pair of FEC

Table I. Parameters for smoothing HRTFs in different planes. I: Smoothing the ipsilateral HRTF only, C: Smoothing the contralateral HRTF only, B: Smoothing the binaural HRTFs.

The horizontal plane, $\theta = 30°, 60°, 90°, 120°, 150°, 210°, 240°, 270°, 300°, 330°$.	
I:	For 0.5 kHz $\leq f <$ 5 kHz, $\Delta f = 1.0$ ERB, for $f \geq$ 5 kHz, $\Delta f = 2.0, 2.5, 3.0$ ERB.
C:	For 0.5 kHz $\leq f <$ 5 kHz, $\Delta f = 1.0$ ERB, for $f \geq$ 5 kHz, $\Delta f = 3.0, 3.5, 4.0$ ERB.
B:	For 0.5 kHz $\leq f <$ 5 kHz, $\Delta f = 1.0$ ERB, for $f \geq$ 5 kHz, Ipsilateral $\Delta f = 2.0$ ERB, Contralateral $\Delta f = 3.5$ ERB.
The lateral plane, $\theta = -30°, 30°, 60°, 120°, 150°, 210°$.	
Γ:	For 0.5 kHz $\leq f <$ 5 kHz, $\Delta f = 1.0$ ERB, for $f \geq$ 5 kHz, $\Delta f = 2.0, 2.5, 3.0$ ERB.
C:	For 0.5 kHz $\leq f <$ 5 kHz, $\Delta f = 1.0$ ERB, for $f \geq$ 5 kHz, $\Delta f = 3.0, 3.5, 4.0$ ERB.
B:	For 0.5 kHz $\leq f <$ 5 kHz, $\Delta f = 1.0$ ERB, for $f \geq$ 5 kHz, Ipsilateral $\Delta f = 2.0$ ERB, Contralateral $\Delta f = 3.5$ ERB.
The median plane, $\theta = -30°, 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°$.	
Phi:	—
C:	—
B:	For 0.5 kHz $\leq f <$ 5 kHz, $\Delta f = 1.0$ ERB, for $f \geq$ 5 kHz, Binaural $\Delta f = 2.0, 2.5, 3.0$ ERB.

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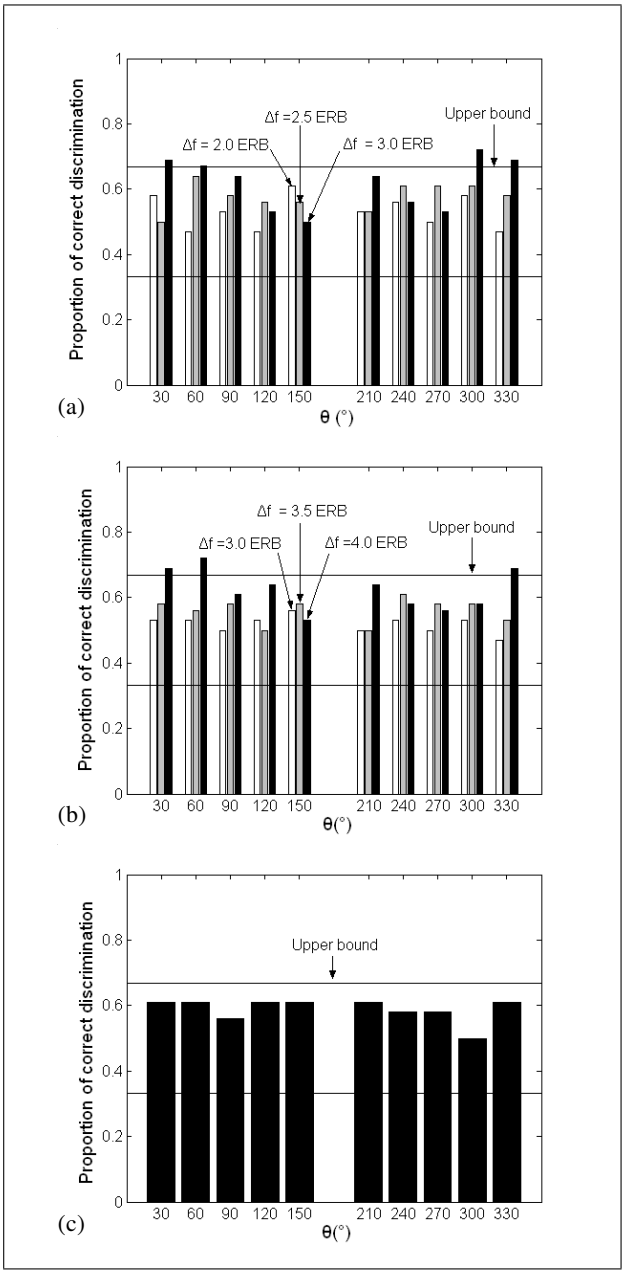


Figure 2. Mean proportions of correct discriminations for smoothing HRTFs in the horizontal plane. (a) Smoothing the ipsilateral HRTF only, (b) Smoothing the contralateral HRTF only, (c) Smoothing both magnitudes of the binaural HRTFs.

headphone (headphone with free-air equivalent coupling to the ear), the binaural sound pressures are nearly equal to that created by an actual sound source. However, the headphone used in the experiment was not exact match for a FEC headphone, but exhibited a deviations of 2–4 dB below 7 kHz [27].

A three-interval, two-alternative forced-choice (3I-2AFC) listening experiment was carried out. Under each given experimental condition (intended direction of sound image, smoothing the ipsilateral, contralateral or binaural HRTFs, bandwidth Δf), the binaural signals created by the original and smoothed HRTFs were used, respectively, as a reference and a target. There were three parts in each trial of signals to be evaluated. The first part was always the reference, and the second and third parts were the reference and the target, respectively, with two different orders: "reference-reference-target" and "reference-target-reference". The duration of each part of the signals was 3 s, including a 0.5 s fade in and a 0.5 s fade out respectively. A 1 s period of silence existed between each part of the signals.

The three parts of the signal in each trial were reproduced consecutively. Subjects discriminated the target signal from the second or the third part of the trial according to any subjective difference, including sound image direction and timbre etc., and recorded the result by a computer. If a subject was unable to discriminate the target signal, he (she) answered randomly. Each kind of signal with two different orders was reproduced three times in a random order. Hence, there were six discriminations by each subject. Six subjects (three male and three female) participated in the experiment. The participants were graduate students or teachers in our laboratory and had previous experience in psychoacoustic experiment. The hearing of each subject was assessed by an audiometry, screening at less than 15 dB HL for frequencies ranging from 125 Hz to 8 kHz in octave steps. Some previous experimental results also showed that the subjects were able to locate the sound source correctly using their individual (original) HRTFs.

Statistical analysis was applied to the experimental results. Under a given experimental condition, a total of 36 discriminations were collected (6 subjects and 6 discriminations from each subject). In the 3I-2AFC experiments, if all of the subjects were unable to discriminate the target signal and thus gave answers randomly, the statistical expected value of the proportion of correct discriminations was $\mu_0 = 0.5$. According to the theory of hypothesis test, at the significance level of $\alpha = 0.05$, if the mean proportion of correct discriminations is within the bounds of (0.337, 0.663), the hypothesis that the proportion of correct discriminations equals to the expected value $\mu_0 = 0.5$ is accepted. Under this condition, subjects are considered to be unable to discriminate the target signal; thereby, artifacts in smoothed magnitudes of HRTFs are inaudible.

3. Experimental results and analysis

3.1. Smoothing HRTFs in the horizontal plane

Figure 2a shows the results of discrimination for smoothing the ipsilateral HRTFs only. For bandwidths of Δf = 2.0 ERB and 2.5 ERB, the mean proportions of correct discriminations at all intended directions were within the bounds. For Δf = 3.0 ERB, the mean proportions of correct discriminations at θ = 30°, 60°, 300°, and 330° exceeded or reached the upper bound of 0.663.

Figure 2b shows the results of discrimination for smoothing the contralateral HRTFs only. For bandwidths of Δf = 3.0 ERB and 3.5 ERB, the mean proportions of correct discriminations at all intended directions were within the

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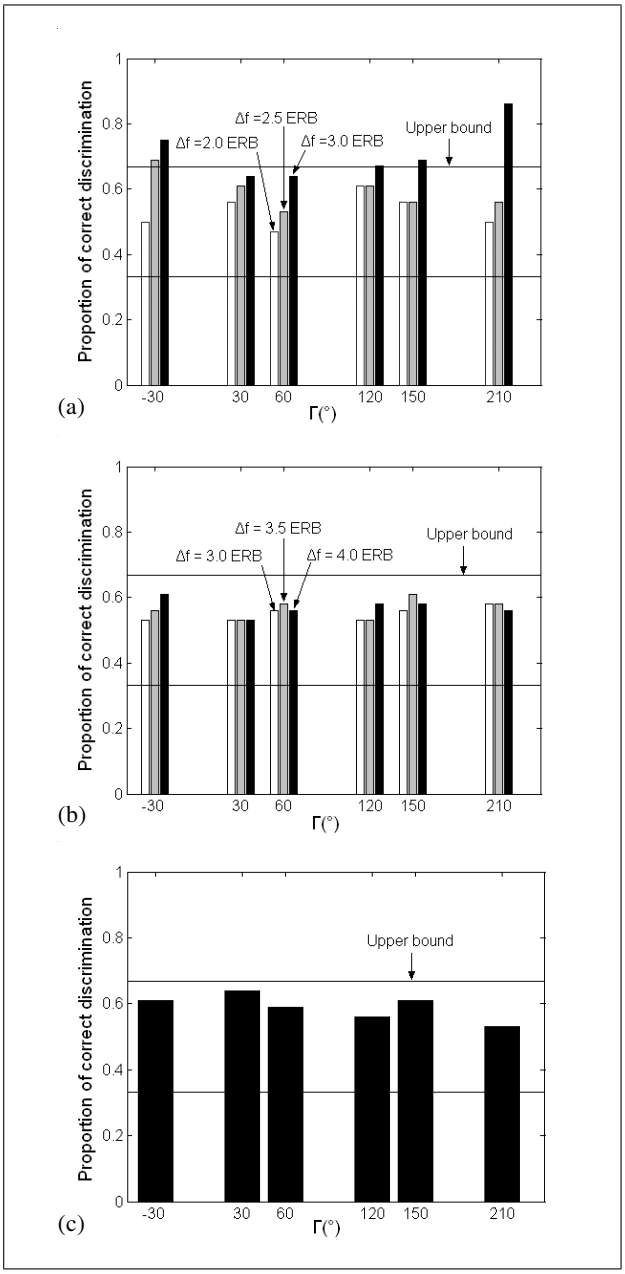


Figure 3. Mean proportions of correct discriminations for smoothing HRTFs in the lateral plane, (a) Smoothing the ipsilateral HRTFs only, (b) Smoothing the contralateral HRTFs only, (c) Smoothing both magnitudes of the binaural HRTFs.

bounds. For $\Delta f = 4.0$ ERB, the mean proportions of correct discriminations at $\theta = 30°$, 60°, and 330° exceeded the upper bound of 0.663.

Therefore, a bandwidth of $\Delta f = 2.0$ ERB was selected for the ipsilateral ear and 3.5 ERB for the contralateral ear in smoothing both magnitudes of the binaural HRTFs. The reason for these selections will be explained in section 3.2.

Figure 2c shows the results of discrimination for smoothing both magnitudes of the binaural HRTFs in the horizontal plane. The mean proportions of correct discriminations at all intended azimuths were within the bounds.

In summary, in the case of the horizontal plane and at the frequencies above 5 kHz,

1. magnitudes of the ipsilateral HRTF can be smoothed only with a bandwidth up to 2.5 ERB without introducing audible artifacts;
2. magnitudes of the contralateral HRTF can be smoothed only with a bandwidth up to 3.5 ERB without introducing audible artifacts;
3. both magnitudes of the binaural HRTFs can be smoothed with bandwidths of 2.0 ERB for the ipsilateral ear and 3.5 ERB for the contralateral ear, respectively, without introducing audible artifacts.

Hence, hearing is insensitive to the spectral detail of HRTF magnitude above 5 kHz, especially for the contralateral HRTF.

3.2. Smoothing HRTFs in the lateral plane

For smoothing the ipsilateral HRTF only, the results of discrimination are shown in Figure 3a. For a bandwidth of 2.0 ERB and at all intended directions Γ, the mean proportions of correct discriminations were within the bounds. For $\Delta f = 2.5$ ERB, the mean proportions of correct discriminations at $\Gamma = -30°$ exceeded the upper bound, and for $\Delta f = 3.0$ ERB, the mean proportions of correct discriminations at $\Gamma = -30°$, 120°, 150° and 210° exceeded or reached the upper bound.

For smoothing the contralateral HRTF only, the results of the discrimination are shown in Figure 3b. For all bandwidths Δf and at all intended directions Γ, the mean proportions of correct discriminations were within the bounds.

Considering all together the results of the horizontal plane in section 3.1 and the lateral plane, the magnitudes of the ipsilateral HRTFs above 5 kHz can be smoothed with a bandwidth up to 2.0 ERB, and the magnitudes of the contralateral HRTFs can be smoothed with a bandwidth up to 3.5 ERB, respectively, without introducing audible artifacts. Hence, in both the horizontal and the lateral planes, a bandwidth of 2.0 ERB was selected for the ipsilateral ear and 3.5 ERB for the contralateral ear in smoothing both magnitudes of the binaural HRTFs above 5 kHz.

The results of discrimination for smoothing both magnitudes of the binaural HRTFs in the lateral plane are shown in Figure 3c. At all intended directions Γ, the mean proportions of correct discriminations were within the bounds.

Hence the results for the lateral plane are similar to that for the horizontal plane. That is, above 5 kHz:

1. magnitudes of the ipsilateral HRTF can be smoothed only with a bandwidth of 2.0 ERB without introducing audible artifacts;
2. magnitudes of the contralateral HRTF can be smoothed only with a bandwidth of 4.0 ERB without introducing audible artifacts.
3. both magnitudes of the binaural HRTFs can be smoothed with bandwidths of 2.0 ERB for the ipsilateral ear and 3.5 ERB for the contralateral ear without introducing audible artifacts.

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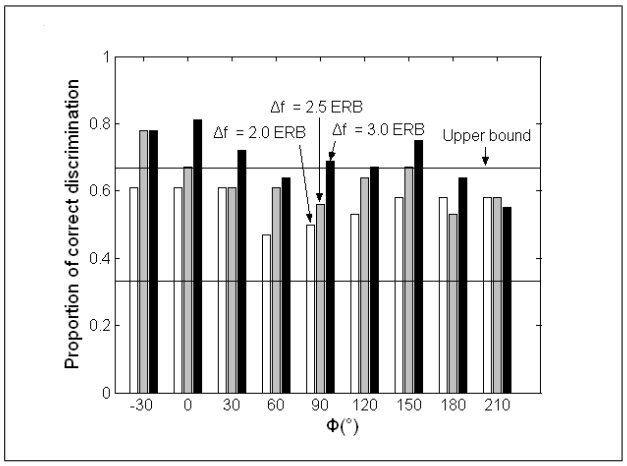


Figure 4. Mean proportions of correct discriminations for smoothing both magnitudes of the binaural HRTFs in the median plane.

3.3. Smoothing HRTFs in the median plane

Only the case of smoothing both magnitudes of the binaural HRTFs with the same bandwidth was considered. The results of discrimination are shown in Figure 4. For a bandwidth of 2.0 ERB, the mean proportions of correct discriminations at all intended directions Φ were within the bounds. For a bandwidth of 2.5 ERB, the mean proportions of correct discriminations at $\Phi = -30°$, 0°, and 150° exceeded or reached the upper bound; and for a bandwidth of 3.0 ERB, the mean proportions of correct discriminations at $\Phi = -30°$, 0°, 30°, 90°, 120°, and 150° exceeded or reached the upper bound. Hence, on average, both magnitudes of the binaural HRTFs above 5 kHz can be smoothed with a bandwidth of 2.0 ERB without introducing audible artifacts.

4. Further analysis of the experimental results

In order to explain the experimental results, in this section, the HRTFs from a subject , No.4, at $\Gamma = -30°$ in the lateral plane (in a direction to the right and slightly lower) are analyzed.

4.1. Analysis on HRTF magnitude spectra

The magnitudes of the original and smoothed HRTFs are shown in Figure 5.

1. Figure 5a shows the ipsilateral (right) HRTF, with the smoothing bandwidth of 2.0 ERB above 5 kHz. Below 5 kHz, the magnitude of the smoothed HRTF was very close to that of the original HRTF, and that most features in the original HRTF were retained in the smoothed HRTF. After being smoothed, however, the notch at 8 kHz became shallow, and the narrow peaks and notches above 10 kHz basically disappeared.
2. Figure 5b also shows the ipsilateral (right) HRTF, with the smoothing bandwidth of 3.0 ERB above 5 kHz. Compared with Figure 5a, the notch at 8 kHz became much more shallow than the original HRTF.
3. Figure 5c shows the contralateral (left) HRTF, with the smoothing bandwidth of 3.5 ERB above 5 kHz. Above 5 kHz, the magnitude of the original HRTF varied rapidly with frequency and exhibited a series of narrow peaks and notches. This is due to the multipath interference of the diffraction sound waves at the contralateral ear. On the whole, the magnitude above

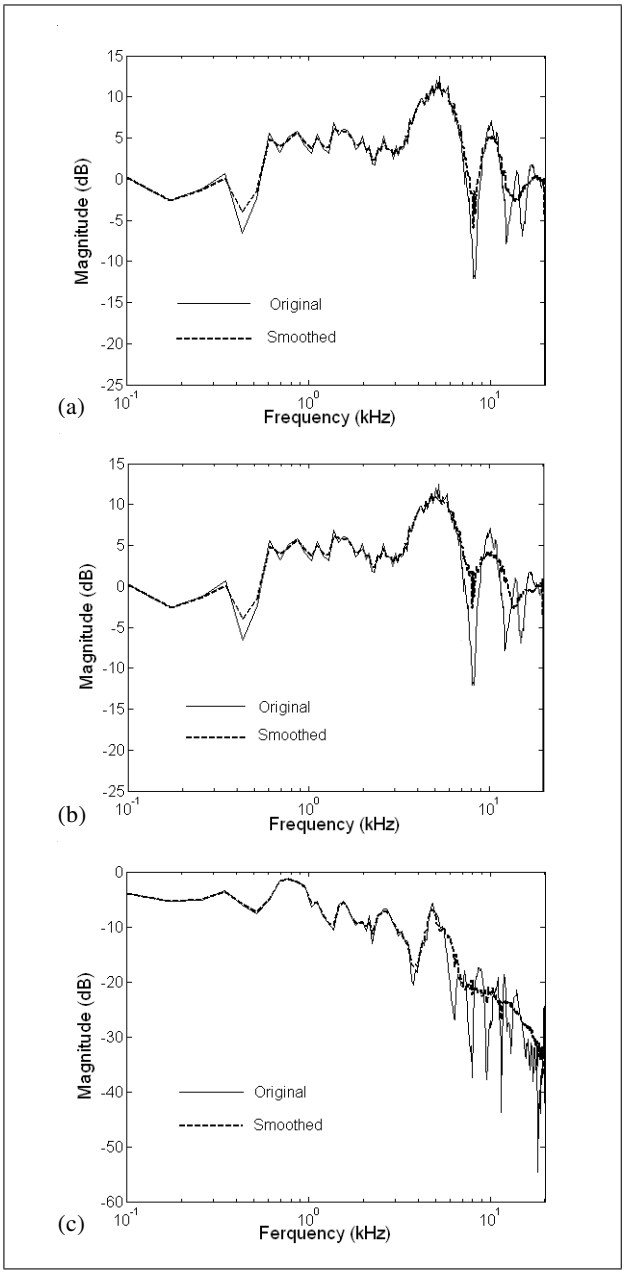


Figure 5. Original and smoothed HRTF magnitudes at $\Gamma = -30°$ in the lateral plane for subject No.4. (a) The ipsilateral HRTF, bandwidths for smoothing are: $\Delta f = 1.0$ ERB for 0.5 kHz $\leq f <$ 5 kHz and $\Delta f = 2.0$ ERB for $f \geq 5$ kHz. (b) The ipsilateral HRTF, bandwidths for smoothing are: $\Delta f = 1.0$ ERB for 0.5 kHz $\leq f < 5$ kHz; and $\Delta f = 3.0$ ERB for $f \geq 5$ kHz. (c) The contralateral HRTF, bandwidths for smoothing are: $\Delta f = 1.0$ ERB for 0.5 kHz $\leq f < 5$ kHz; and $\Delta f = 3.5$ ERB for $f \geq 5$ kHz.

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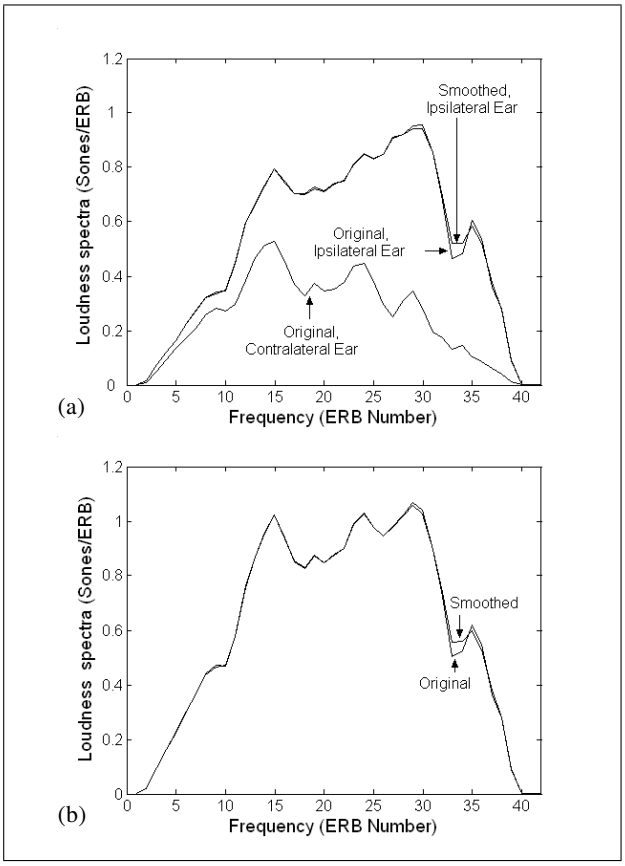


Figure 6. Loudness spectra for smoothing the ipsilateral HRTF only. Bandwidths for smoothing are: $\Delta f = 1.0$ ERB for 0.5 kHz $\leq f < 5$ kHz; and $\Delta f = 2.0$ ERB for $f \geq 5$ kHz. (a) Monaural loudness spectra, (b) Binaural loudness spectra.

5 kHz is attenuated greatly due to the shadow effect of the head. After being smoothed, the rapid fluctuation of magnitude at high frequency vanished.

4.2. Analysis of the loudness spectra

The analysis above was based on physical criteria. Further analysis was based on certain auditory criteria.

Smoothing the magnitudes of the HRTFs modifies the monaural or binaural magnitude spectra in the virtual auditory display, and hence modifies the monaural or binaural loudness spectra. A certain extent of changes in loudness spectra will cause some audible artifacts. In fact, both perceived timbre and total loudness depend on the binaural loudness spectra. The perceived direction of a sound image is closely related to the monaural or binaural loudness spectra as well as the interaural loudness level spectra difference which corresponds to the interaural level difference ILD. All the changes in these perceived items can be used to discriminate the smoothed HRTFs from the original ones in the 3I 2AFC experiment.

Huopaniemi and Zacharov [15] and Pulkki *et al.* [28] used a binaural auditory model and Zwicker's loudness formula [29] to calculate the loudness level spectra in the stereophonic reproduction and the virtual auditory display. In this research, the loudness model of Moore and colleagues [30, 31, 32] was used to analyze the monaural and binaural loudness spectra recreated by the original and smoothed HRTFs, respectively. An outline of the calculation can be found in the Appendix.

In the following, SL_I denotes the monaural loudness spectra, or specific loudness, for the ipsilateral ear; SL_C denotes the monaural loudness spectra for the contralateral ear; SL_B denotes the binaural loudness spectra; and ILLD denotes the interaural loudness level spectra difference.

4.2.1. Smoothing the ipsilateral HRTF only with a bandwidth of 2.0 ERB

For the high-frequency smoothing of 2.0 ERBs, Figure 6a shows, respectively, the SL_I for the original and smoothed ipsilateral (right) HRTF. The figure also shows the SL_C for the original contralateral (left) HRTF.

Near the frequency of 33 ERB Number, the SL_I exhibited a notch which corresponds to the notch in the HRTF magnitude at 8 kHz. And at the frequency of 33 ERB number, the SL_I for the original and smoothed HRTFs were, respectively, 0.47 Sones/ERB and 0.52 Sones/ERB, or equivalently, 31.2 Phons/ERB and 32.3 Phons/ERB. A 1.1 Phons/ERB difference existed between them. Interestingly, the notch at 33 ERB Number became shallow but still survived after the smoothing process. With this exception, the SL_I for the smoothed HRTF was much closer to that for the original HRTFs. According to Figure 6a, the ILLD can be calculated. At the frequency of 33 ERB Number, the results were 11.8 Phons/ERB for the original HRTF and 12.9 Phons/ERB for the smoothed HRTF, respectively, with the difference between them being equal to 1.1 Phons/ERB.

Figure 6b shows the corresponding SL_B, whose value is similar to that of SL_I. At the frequency of 33 ERB number, the SL_B for original and smoothed HRTFs were 0.50 Sones/ERB (31.8 Phons/ERB) and 0.56 Sones/ERB (33.1 Phons/ERB), respectively, with the difference between them being 1.3 Phons/ERB. In addition, the evaluated results from Figure 6b indicated that the overall binaural loudness for both original and smoothed HRTFs was 25.5 Sones (86.4 Phons). The precision of the calculation indicated no difference between them.

The average just-noticeable difference (JND) in the binaural loudness level spectra is generally hypothesized to be approximately equal to 1 Phon/ERB. The results obtained in this research indicate that the maximal difference between the binaural loudness spectra of the smoothed and original HRTFs just reaches or slightly exceeds the JND. The JND is defined as the point at which the probability of discrimination is 50% (practically, in the 3I 2AFC experiment, correct discrimination should be 75%). Considering that the threshold of discrimination changes considerably among individuals, so for a given subject, a difference of BLLS near the mean JND may be audible or not. In fact, in this case, the subject (No.4) could not discriminate the smoothed HRTF from the original one in the discrimination experiment described in section 3.2, and gave the answer randomly.

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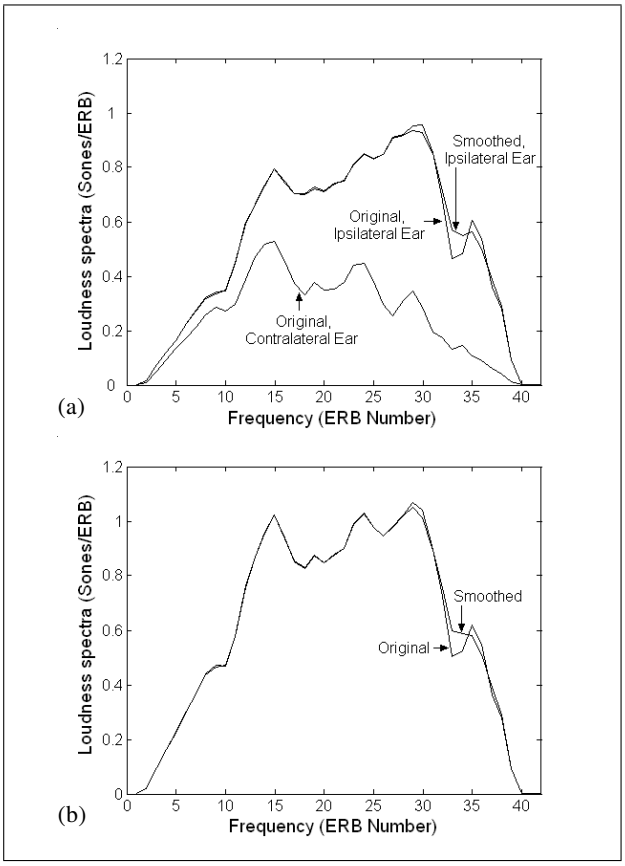


Figure 7. Loudness spectra for smoothing the ipsilateral HRTF only. Bandwidths for smoothing are: $\Delta f = 1.0$ ERB for 0.5 kHz $\leq f < 5$ kHz; and $\Delta f = 3.0$ ERB for $f \geq 5$ kHz. (a) Monaural loudness spectra, (b) Binaural loudness spectra.

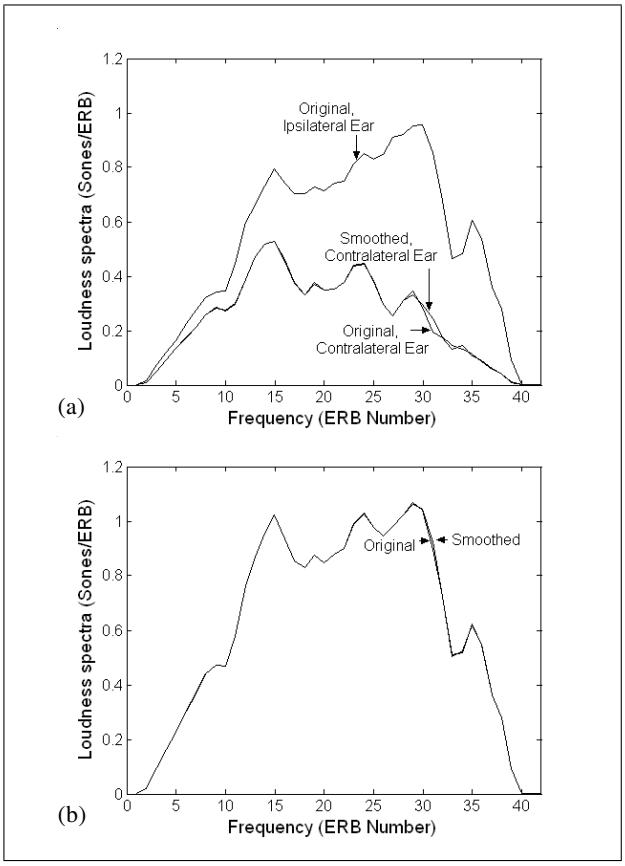


Figure 8. Loudness spectra for smoothing the contralateral HRTF only. Bandwidths for smoothing are: $\Delta f = 1.0$ ERB for 0.5 kHz $\leq f < 5$ kHz; and $\Delta f = 3.5$ ERB for $f \geq 5$ kHz. (a) Monaural loudness spectra, (b) Binaural loudness spectra.

4.2.2. Smoothing the ipsilateral HRTF only with a bandwidth of 3.0 ERB

For high-frequency smoothing of 3.0 ERBs, Figures 7a and 7b, respectively, illustrate the SL_I and corresponding SL_B. As a whole, the results in Figure 7 are similar to those in Figure 6. However, at the frequency of 33 ERB number and for both SL_I and SL_B, the difference between the results for the original and smoothed HRTFs becomes 2.1 Phons/ERB which is approximately twice the value of the JND, and the notch almost vanished.

The increasing difference in loudness spectra may cause some audible artifacts. In fact, in this case, all six judgments from subject No.4 in the discrimination experiment described in Sec 3.2 were correct. The subject reported that she discriminated the smoothed HRTF from the original one by the difference in timbre.

4.2.3. Smoothing the contralateral HRTF only with a bandwidth of 3.5 ERB

For high-frequency smoothing of 3.5 ERBs, Figure 8a shows the SL_C, respectively, for the original and smoothed contralateral (left) HRTFs, and also shows the SL_I for the original ipsilateral HRTF.

Near the frequency of 31 ERB Number, a difference of 2.0 Phons/ERB was observed between the SL_C for the smoothed HRTF and that for the original one. At the frequency of 31 ERB Number, the difference was 2.0 Phons/ERB. With this exception, the SL_C for the smoothed HRTF was very close to that of the original one. Figure 5c shows that distinct differences exist between the magnitudes of the original and the smoothed contralateral HRTFs at high frequency. However, due to the limited (cochleae) frequency resolution used in calculating the loudness spectra, the rapid fluctuation of the original HRTF magnitude at high frequency was smoothed. Accordingly the difference between the SL_C for the original HRTF and the smoothed HRTF diminished. Similarly, we can also calculate the ILLD. For brevity, however, the results are omitted here.

Figure 8b shows the corresponding SL_B. The result for the smoothed HRTF was very close to that of the original HRTF. Even at the frequency of 31 ERB number, the difference was only 0.3 Phons/ERB. In fact, due to the shadow effect of the head, the contralateral HRTF magnitude is attenuated obviously above 5 kHz. Consequently, the contribution of the contralateral loudness spectra to the binaural loudness spectra at high frequency is slight. Therefore, even if smoothing causes some change in the contralateral loudness spectra at high frequency, the binaural loudness spectra is almost unchanged. In addition, the

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evaluated results from Figure 8b indicated that the overall binaural loudness for both the original and smoothed HRTFs was 25.5 Sones (86.4 Phons).

From this analysis, some differences are indicated between the contralateral loudness spectra for the smoothed and original HRTFs at and near the frequency of 31 ERB Number. However, compared with the spectral cues provided by the ipsilateral HRTF, the contribution of the contralateral HRTF to localization is slight [20, 21]. The almost unchanged binaural loudness spectra indicate that the timbre is intact after being smoothed. As a whole, smoothing HRTFs should not cause audible artifacts. In fact, in this case, the subject (No.4) could not discriminate the smoothed HRTF from the original one in the discrimination experiment described in section 3.2, and gave a random response.

4.2.4. Smoothing the both magnitudes of the binaural HRTFs

In the case of the high-frequency smoothing of 2.0 ERB for the ipsilateral HRTF and 3.5 ERB for the contralateral HRTF, the monaural loudness spectra are identical to those shown respectively in Figure 6a and Figure 8a. For brevity, the SL_B curves are omitted here. However the results showed that the SL_B for the smoothed HRTF was very close to that for the original one. The maximal difference between them was only 1.3 Phons/ERB at 33 ERB Number which is insignificant. In addition, the evaluated results also indicated that the overall binaural loudness for both the original and smoothed HRTFs was 25.5 Sones (86.4 Phons). In this case, the subject (No.4) could not discriminate the smoothed HRTF from the original HRTF in the discrimination experiment described in section 3.2, and gave a random response.

Although only a single case from a subject and at a given spatial direction is analyzed here, the results for other subjects and other spatial directions are similar to this case. Generally, the audibility of smoothing HRTF magnitudes depends on the difference of the loudness spectra between the original and smoothed HRTFs. If the difference is not obvious, the smoothing artifacts are inaudible. Otherwise, they are audible. Moreover, the contribution of the ipsilateral loudness spectra to audibility is greater than that of the contralateral loudness spectra. HRTFs are individual-dependent, however. Even at the same spatial direction, considerable differences exist among the HRTFs from different subjects. Moreover, the hearing may vary from person to person. Therefore, the audibility of smoothing artifacts may be dependent on the subject. The statistical results from only a few subjects were obtained in this study and the qualitative analysis is given in this section. More elaborate results should be based on a larger group of subjects, and this is our future work.

5. Conclusion

The results of psychoacoustic experiments in this research indicated that the spectral detail of HRTF magnitude at high frequency was inaudible. Considering both the horizontal and lateral planes, the ipsilateral and contralateral HRTF magnitudes above 5 kHz could be smoothed only with a bandwidth up to 2.0 ERB and 3.5 ERB, respectively, without introducing audible artifacts. Both the magnitudes of the binaural HRTFs above 5 kHz could also be smoothed with a bandwidth of 2.0 ERB for the ipsilateral ear and 3.5 ERB for the contralateral ear, respectively. Accordingly, hearing is less sensitive to the spectral detail in the contralateral HRTF magnitude. In the median plane, both magnitudes of the binaural HRTF above 5 kHz could be smoothed with a bandwidth of 2.0 ERB without introducing audible artifacts. The audibility of the smoothed HRTF magnitude depended on the difference of loudness spectra between the original and smoothed HRTFs, such that the result is individual-dependent. In practical signal processing of a virtual auditory display, it is unnecessary to use complex signal models to represent the spectral detail in HRTF magnitudes at high frequency, especially for the contralateral HRTFs.

Because these results were based on only six subjects, the conclusion is preliminary. Further psychoacoustic experiments with more subjects are needed before reaching a more general conclusion.

Appendix

Calculating the loudness spectra by using the loudness model

The original loudness model by Moore and colleagues [30] was based on Zwicker's loudness model [29] and formed the basis for an ANSI standard for loudness calculation [31]. Moore and colleagues proposed a modified model to calculate binaural loudness in 2007 [32]. The details of the model can be found in the literatures cited above. The process for calculating the monaural and binaural loudness for the original or smoothed HRTFs by the loudness model of Moore and colleagues is outlined here.

Scale the input stimulus

A mono white noise was used as the input stimulus. The stimulus was scaled such that its root-mean square (RMS) value of 1 corresponded to a pressure level of 0 dB in the free field (measured at the center of the head with the head absent). Here, the stimulus was scaled to corresponding to a pressure level of 70 dB in the free field, which was equivalent to the sound pressure levels presented in the experiment described in section 2.2.

Transfer through the external and middle ear

In order to simulate the transfer through the external ear, the scaled stimulus was filtered by a pair of (original or smoothed) individual HRTFs. Because the HRTFs were measured at the blocked entrance of the ear canal, an ear canal filter should be appended so as to obtain the pressure signal at the eardrum. The transfer function from the blocked entrance of the ear canal to the eardrum is individual-dependent. Limited by the experimental conditions, however, individual ear canal filters were not used.

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Instead, a mean ear canal filter was used as was suggested by Hammershi *et al.* [33]. Then the pressure signal at the eardrum was filtered by the middle ear transfer function specified by the ANSI S3.4-2007 standard, resulting in the physical spectra reaching the cochlea.

Calculation of the excitation patterns at the cochlea

The frequency selectivity of the cochlea was modeled by a bank of band-pass filters with different center frequencies. The characters of cochlea filters were specified by ANSI S3.4-2007. Cochlea filters transformed the physical spectra to excitation patterns E_{sig}.

Transform to monaural specific loudness

The excitation patterns, E_{sig}, were transformed to monaural specific loudness (loudness spectra) SL in units of Sones/ERB by the loudness formula of Moore and colleagues [30, 31].

Calculation the binaural specific loudness

The inhibitory interactions between the two ears were taken into account in the modified binaural loudness model by Moore and colleagues [32]. The original monaural specific loudness of the left and right ear obtained in step (4) was used to calculate the inhibition factor for the left and right ear, respectively, and, subsequently, to obtain binaural specific loudness (binaural loudness spectra) SL_B in units of Sones/ERB.

Calculation of the overall loudness

The binaural specific loudness was summed across frequency to obtain the overall binaural loudness in units of Sones.

Transform to loudness level

The specific loudness obtained in steps (4) and (5) was transformed to specific loudness level (loudness level spectra) in units of Phons/ERB. Subsequently the interaural loudness level (spectra) difference ILLD which is the difference between the specific loudness level of the right and left ear was calculated. Similarly, the overall loudness obtained in step (6) was also transformed to the overall loudness level in units of Phons.

Acknowledgements

The authors acknowledge the support of the National Nature Science Fund of China Grant No. 10774049 and the State Key Lab of Subtropical Building Science, South China University of Technology. The authors also thank Dr. Xiaoli Zhong for her assistance.

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