Available online at www.sciencedirect.com
ScienceDirect
Applied Acoustics 68 (2007) 835–850
applied acoustics
www.elsevier.com/locate/apacoust

Median plane localization using a parametric model of the head-related transfer function based on spectral cues

Kazuhiro Iida [a,*], Motokuni Itoh [a], Atsue Itagaki [b], Masayuki Morimoto [b]

[a] AV Core Technology Development Center, Matsushita Electric Industrial Co. Ltd., 600 Saedo, Tsuzuki, Yokohama 224-8539, Japan
[b] Environmental Acoustics Laboratory, Faculty of Engineering, Kobe University, Kobe, Japan

Received 6 March 2006; received in revised form 11 July 2006; accepted 19 July 2006
Available online 28 November 2006

Abstract

To examine a simulation method for vertical sound localization, and to clarify which peaks and notches in head-related transfer functions (HRTFs) play a role as spectral cues, localization tests in the median plane were carried out using a parametric HRTF model, which is recomposed only of extracted spectral peaks and notches. The results show that the parametric HRTF recomposed using the first and second notches (N1 and N2) and the first peak (P1) provides almost the same localization accuracy as the measured HRTFs. Observations of the spectral peaks and notches indicate that N1 and N2 change remarkably as the source elevation changes, whereas P1 does not depend on the source elevation. In conclusion, N1 and N2 can be regarded as spectral cues, and the hearing system could utilize P1 as the reference information to analyze N1 and N2.

Keywords: Head-Related transfer function; Spectral cue; Sound localization; Spectral peak; Spectral notch; The median plane

* Corresponding author. Tel.: +81 45 939 1905.
E-mail address: iida.kazuhiro@jp.panasonic.com (K. Iida).

0003-682X/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apacoust.2006.07.016

1. Introduction

It is generally known that spectral information is a cue for median plane localization. Most previous studies showed that spectral distortions caused by pinnae in the high-frequency range approximately above 5 kHz act as cues for median plane localization [1–11]. Mehrgardt and Mellert [7] have shown that the spectrum changes systematically in the frequency range above 5 kHz as the elevation of a sound source changes. Shaw and Teranishi [2] reported that a spectral notch changes from 6 to 10 kHz when the elevation of a sound source changes from −45 to 45°. Iida et al. [11] carried out localization tests and measurements of head-related transfer functions (HRTFs) with the occlusion of the three cavities of pinnae, scapha, fossa, and concha. Then they concluded that spectral cues in median plane localization exist in the high-frequency components above 5 kHz of the transfer function of concha.

Hebrank and Wright [5] carried out experiments with filtered noise and reported the following: spectral cues of median plane localization exist between 4 and 16 kHz; front cues are a 1-octave notch having a lower cutoff frequency between 4 and 8 kHz and increased energy above 13 kHz; an above cue is a 1/4-octave peak between 7 and 9 kHz; a behind cue is a small peak between 10 and 12 kHz with a decrease in energy above and below the peak. Moore et al. [12] measured the thresholds of various spectral peaks and notches. They showed that the spectral peaks and notches that Hebrank and Wright regarded as the cues of median plane localization are detectable for listeners, and thresholds for detecting changes in the position of sound sources in the frontal part of the median plane can be accounted for in terms of thresholds for the detection of differences in the center frequency of spectral notches.

Butler and Belendiuk [6] showed that the prominent notch in the frequency response curve moved toward the lower frequencies as the sound source moved from above to below the aural axis in the frontal half of the median plane. Raykar et al. [13] noted that one of the prominent features observed in the head-related impulse response (HRIR) and one that has been shown to be important for elevation perception are the deep spectral notches attributed to the pinna. They proposed a method of extracting the frequencies of pinna spectral notches from the measured HRIR, distinguishing them from other confounding features. The extracted notch frequencies are related to the physical dimensions and shape of the pinna.

Many studies have been performed on the simulation methods for sound localization [14–20]. Morimoto and Ando [14] had demonstrated that the simulation of sound localization could be accomplished as long as HRTFs were accurately reproduced. Kendall and Rodgers [15] simulated HRTFs with four features; one peak, two notches, and the attenuation of the high-frequency components, using the simple two-pole, four-zero digital filter. However, they did not show any evidence whether the simulation provided accurate localization or not. Asano et al. [16] carried out median plane localization tests with the HRTFs smoothed by ARMA models through headphones. The results of this study indicate that major cues for judgment of elevation angle exist in the high-frequency region above 5 kHz, and that the information in macroscopic patterns is utilized instead of that in small peaks and dips.

The results of these previous studies imply that spectral peaks and notches due to the transfer function of concha in the frequency range above 5 kHz prominently contribute to the perception of sound source elevation. Furthermore, there might be a potential of HRTF modeling based on the knowledge on spectral cues.

The present paper has two purposes. One is to examine a simulation method for localizing a sound image. Authors propose a parametric HRTF model to simulate vertical sound localization. The parametric HRTF is recomposed only of the spectral peaks and notches extracted from the measured HRTF, and the spectral peaks and notches are expressed parametrically with center frequency, level, and sharpness. The other purpose is to clarify the contribution of each spectral peak and notch as a spectral cue. Localization tests are carried out in the upper median plane using the subjects' own measured HRTFs and the parametric HRTFs with various combinations of spectral peaks and notches.

2. Method of recomposing parametric HRTFs

In this section, the method of recomposing the parametric HRTFs is described in detail.

2.1. Measurements of HRTFs

The subjects' own HRTFs in the upper median plane were measured in an anechoic chamber in 30° steps. The distance from the sound sources to the center of the subject's head was 1.5 m. Ear-microphones [21] were used in the HRTF measurements. The ear-microphones were fabricated using the subject's ear molds. Miniature electret condenser microphones of 5 mm diameter (Panasonic WM64AT102) and silicon resin were put into the ear canals of the ear molds and consolidated. In the HRTF measurements, the ear-microphones were put into the ear canals of the subject. The diaphragms of the microphones were located at the entrances of the ear canals. Therefore, this is so called the "meatus-blocked condition" [2], in other words, the "blocked entrances condition" [22].

A maximum length sequence signal was emitted by a loudspeaker in the upper median plane, and the output signals of the ear-microphones were led to a computer (Panasonic CF-R3). The HRTF, $H_{\mathrm{l,r}}(\omega)$, was obtained by

$$H_{\mathrm{l,r}}(\omega) = G_{\mathrm{l,r}}(\omega)/F(\omega), \tag{1}$$

where $F(\omega)$ is the Fourier transform of the waveform, $f(t)$, measured at the point corresponding to the center of the subject's head in the anechoic chamber without a subject, and $G_{\mathrm{l,r}}(\omega)$ is that measured at the entrance of the ear canal of the subject with the ear-microphones.

2.2. Extraction of spectral peaks and notches

As mentioned above, the spectral peaks and notches in the frequency range above 5 kHz prominently contribute to the perception of sound source elevation. Therefore, the spectral peaks and notches are extracted from the measured HRTFs regarding the peaks around 4 kHz, which are independent of sound source elevation [2], as a lower frequency limit. Then, labels are put on the peaks and notches in order of frequency (e.g., P1, P2, N1, N2 and so on). The peaks and notches are expressed parametrically with center frequency, level, and sharpness. The amplitude of the parametric HRTF is recomposed of all or some of these spectral peaks and notches.

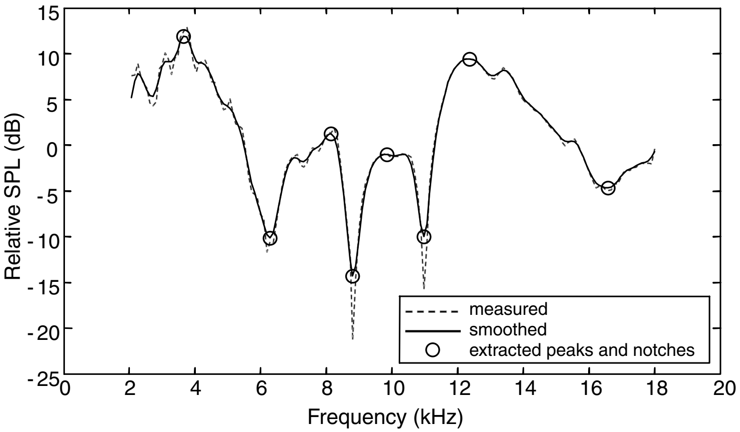

Fig. 1. Examples of extracted spectral peaks and notches from measured HRTF.

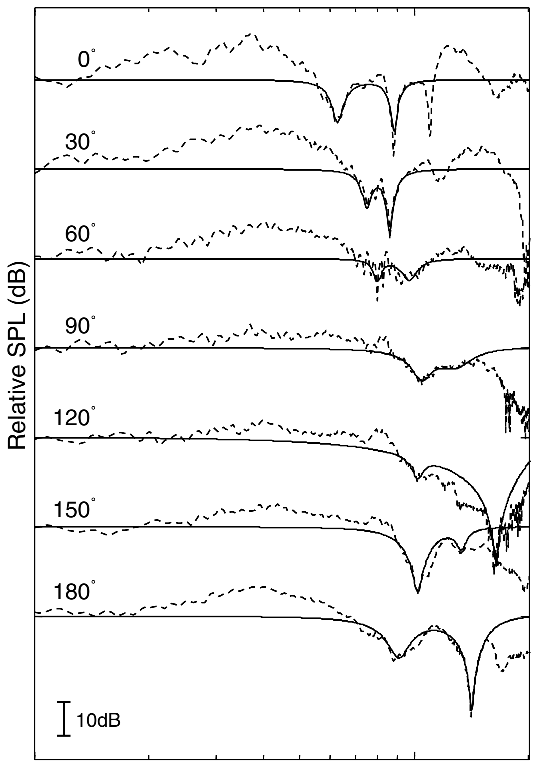

Fig. 2. Examples of measured HRTFs (broken line) and parametric HRTFs recomposed of N1 and N2 (solid line) in the median plane.

In order to extract the essential spectral peaks and notches, the microscopic fluctuations of the amplitude spectrum of HRTF were eliminated by Eq. (2):

$$\mathrm{HRTF}_w(k) = \sum_{n=-n_1}^{n_1} \mathrm{HRTF}(k+n)W(n), \tag{2}$$

where $W(n)$ is a Gaussian filter defined by Eq. (3). k and n denote discrete frequency. The sampling frequency was 48 kHz, and the duration of HRTFs was 512 samples. In this study, n and σ were set to be 4 and 1.3, respectively.

$$W(n) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-n^2}{2\sigma^2}} \tag{3}$$

The spectral peak and notch are defined as the maximal and minimal levels of HRTF_w, respectively. Thus, the center frequencies and the levels of the spectral peaks and notches are obtained. The sharpness of the peak and notch is set to be their envelopment fit with that of HRTF_w. Examples of the extracted spectral peaks and notches are shown in Fig. 1.

Fig. 2 shows examples of the parametric HRTFs recomposed of N1 and N2 in the median plane. As shown in the figure, the parametric HRTF reproduces all or some of the spectral peaks and notches accurately and has flat spectrum characteristics in other frequency ranges.

3. Localization test I

Localization tests in the upper median plane were carried out using the subjects' own measured HRTFs and the parametric HRTFs.

3.1. Method

3.1.1. Subjects

Subjects were two males, 30 and 44 years of age, with a normal hearing sensitivity. They were experienced in this type of localization test.

3.1.2. Apparatus and stimuli

The localization tests were conducted in a quiet listening room. The working area of the chamber was 8.0 m wide, 8.0 m deep, and 3.0 m high. The background noise level was below 20 dB(A). A notebook computer (Panasonic CF-R3), an audio interface (RME Hammerfall DSP), open-air headphones (AKG K1000), and the ear-microphones mentioned above were used for the localization tests, as shown in Fig. 3.

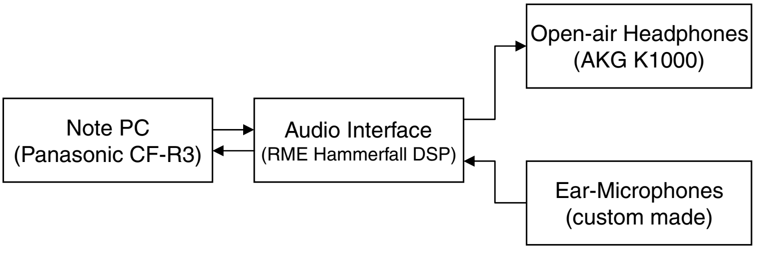

Fig. 3. Apparatus for localization tests.

The subjects sat at the center of the listening room. The ear-microphones were put into the ear canals of the subject. The diaphragms of the microphones were located at the entrances of the ear canals in the same way as in the HRTFs measurements. Then, the subjects wore the open-air headphones, and the stretched-pulse signals were emitted through them. The signals were received by the ear-microphones, and the transfer functions between the open-air headphones and the ear-microphones were obtained. Then, the ear-microphones were removed, and stimuli were delivered through the open-air headphones. Stimuli $P_{l,r}(\omega)$ were created by Eq. (4):

$$P_{l,r}(\omega) = S(\omega) \cdot H_{l,r}(\omega)/C_{l,r}(\omega), \tag{4}$$

where $S(\omega)$ and $H_{l,r}(\omega)$ denote the source signal and HRTF, respectively. $C_{l,r}(\omega)$ is the transfer function between the open-air headphones and the ear-microphones.

The source signal was a wide-band white noise from 280 Hz to 17 kHz. The measured subjects' own HRTFs and the parametric HRTFs in the upper median plane in 30° steps were used. The parametric HRTFs of all the combinations of all or some of the spectral peaks and notches were prepared. However, P1 was not used in the tests except in the combination consisting of all the peaks and notches, since P1 did not have a directional dependence and seemed to have a small contribution to the perception of elevation. For comparison, stimuli without an HRTF convolution, that is, stimuli with $H_{l,r}(\omega) = 1$, were included in the tests.

3.1.3. Procedure

A stimulus was delivered at 60 dB SPL, triggered by hitting a key of the notebook computer. The duration of the stimulus was 1.2 s, including the rise and fall times of 0.1 s, respectively. A circle and an arrow, which indicated the median and horizontal planes, respectively, were shown on the display of the notebook computer. The subject's task was to plot the perceived elevation on the circle, by clicking a mouse, on the computer display. The subject could hear each stimulus over and over again. However, after he plotted the perceived elevation and moved on to the next stimulus, the subject could not return to the previous stimulus. Each stimulus set contained 100 and 68 different stimuli for subjects IT and ID, respectively. The difference in the number of stimuli was due to the differences in the numbers of spectral peaks and notches between subjects. Ten such sets were prepared for the test. The order of presentation of stimuli depended on the test.

3.2. Results

Figs. 4 and 5 show the distributions of the subjects' responses. The diameter of each circle plotted is proportional to the number of responses within 5°. The ordinate of each panel represents the perceived elevation, and the abscissa, the kind of stimulus. The 0° is ahead of the listener, and the 180° is behind. Hereafter, the measured HRTF and parametric HRTF are expressed as the mHRTF and pHRTF, respectively.

For the stimuli without an HRTF, the perceived elevation was not accurate, and the variance of responses was large. On the other hand, the subjects perceived the elevation of a sound source accurately at all the target elevations for the mHRTF. This means that the method and system of the localization tests are adequate.

For the pHRTF(all), which is the parametric HRTF recomposed of all the spectral peaks and notches, the perceived elevation was as accurate as that for the mHRTF at

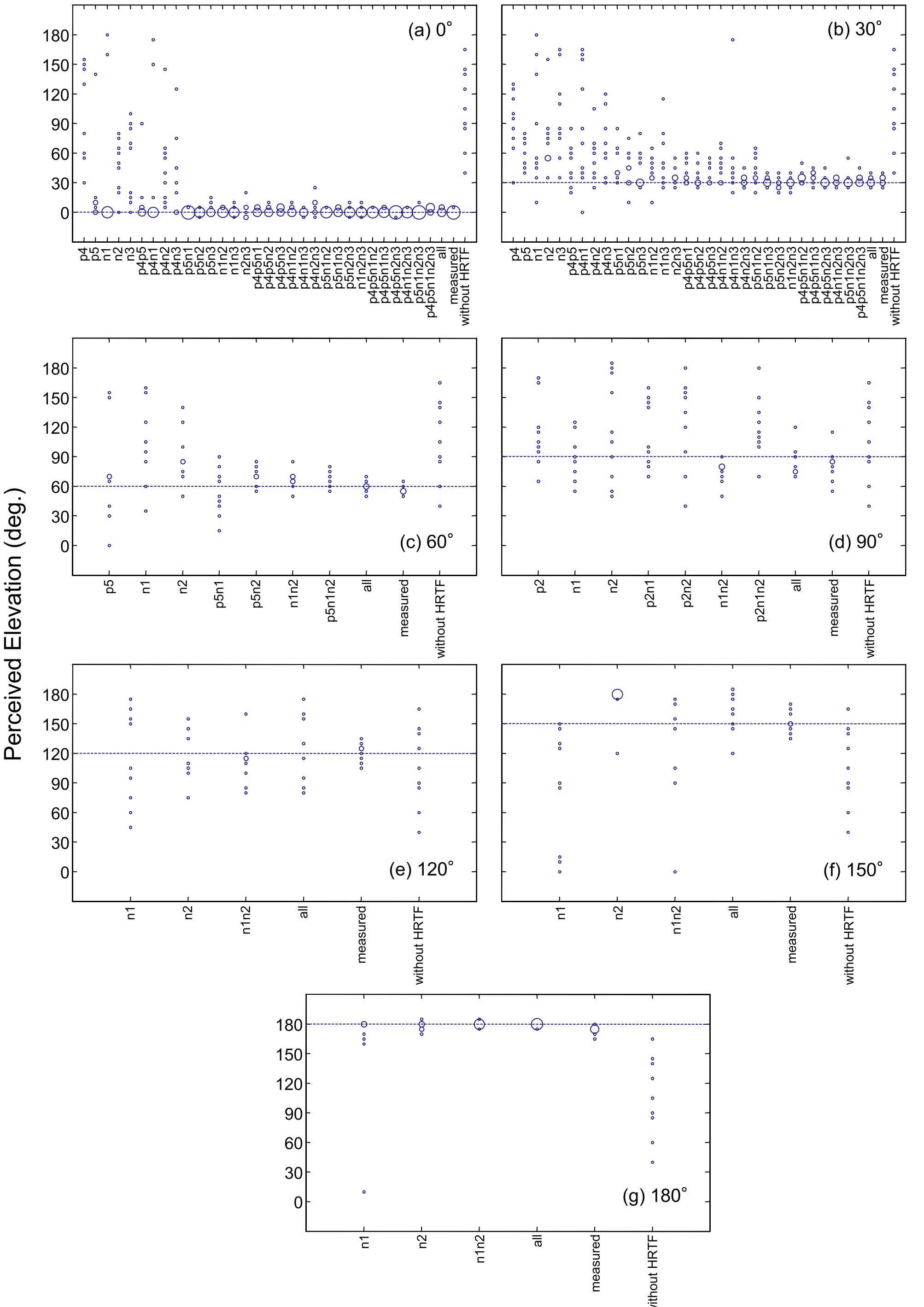

Fig. 4. Localization responses of subject IT for each target elevation. The diameter of the data points indicates the number of responses.

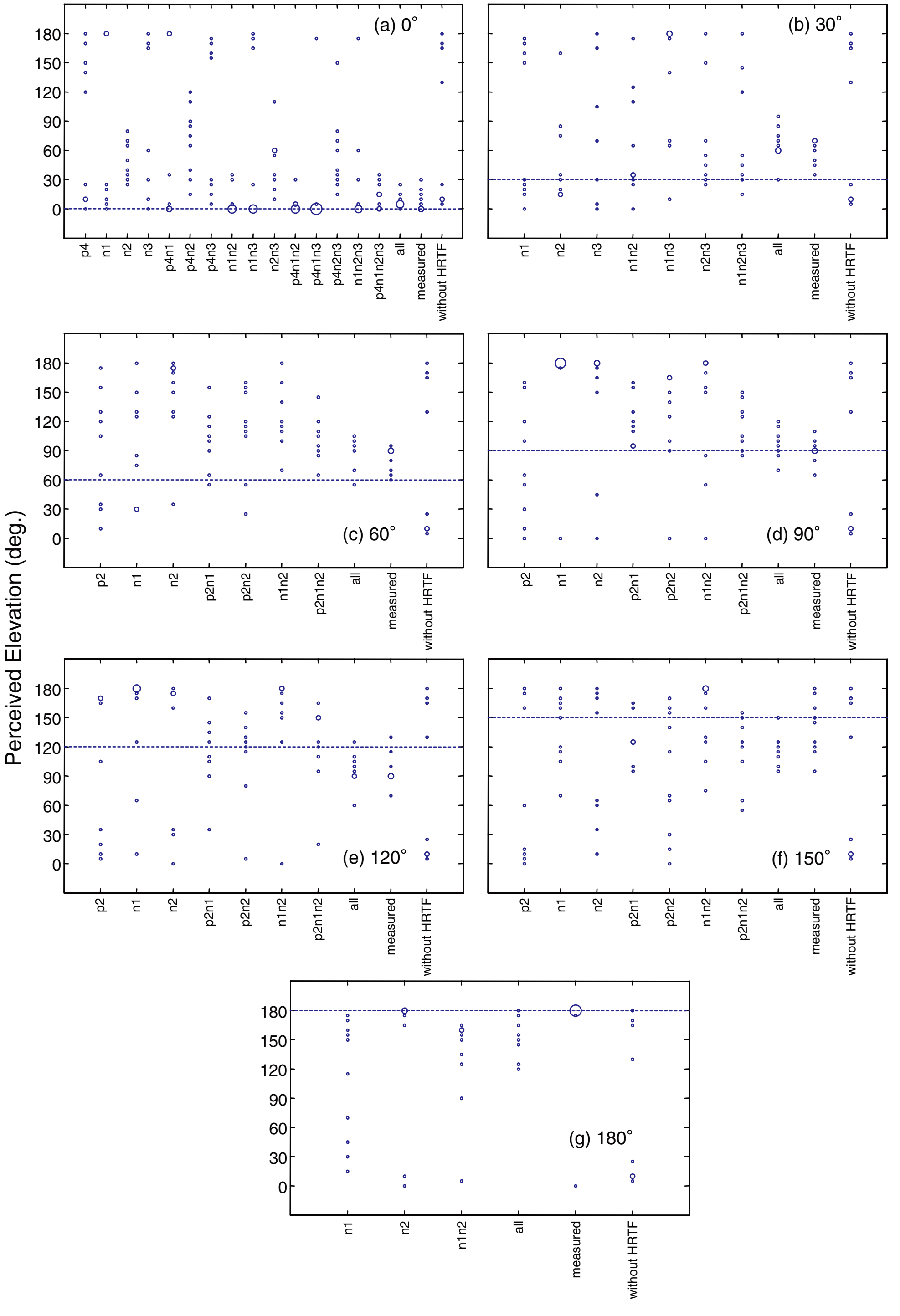

Fig. 5. Localization responses of subject ID for each target elevation.

all the target elevations. In other words, the elevation of a sound source can be perceived correctly when the amplitude spectrum of the HRTF is reproduced by the spectrum peaks and notches. For the pHRTF recomposed of only one spectral peak or notch, the variances of the responses were large at all the target elevations. One peak or notch did not provide sufficient information for localizing the elevation of a sound source. The accuracy of localization improved as the numbers of peaks and notches increased. Careful observation of the results indicates that the pHRTF recomposed of N1 and N2 provides almost the same accuracy of elevation perception as the mHRTF at most of the target elevations.

Fig. 6 shows the responses to the mHRTF, pHRTF(all), and pHRTF(N1–N2) for seven target elevations. The ordinate of each panel represents the perceived elevation, and the abscissa, the target elevation. The diameter of each circle plotted is proportional to the number of responses within five degrees. For the pHRTF(all), the responses distribute along a diagonal line, and this distribution is practically the same as that for the mHRTF. For the pHRTF(N1–N2), the responses distribute along a diagonal line, in

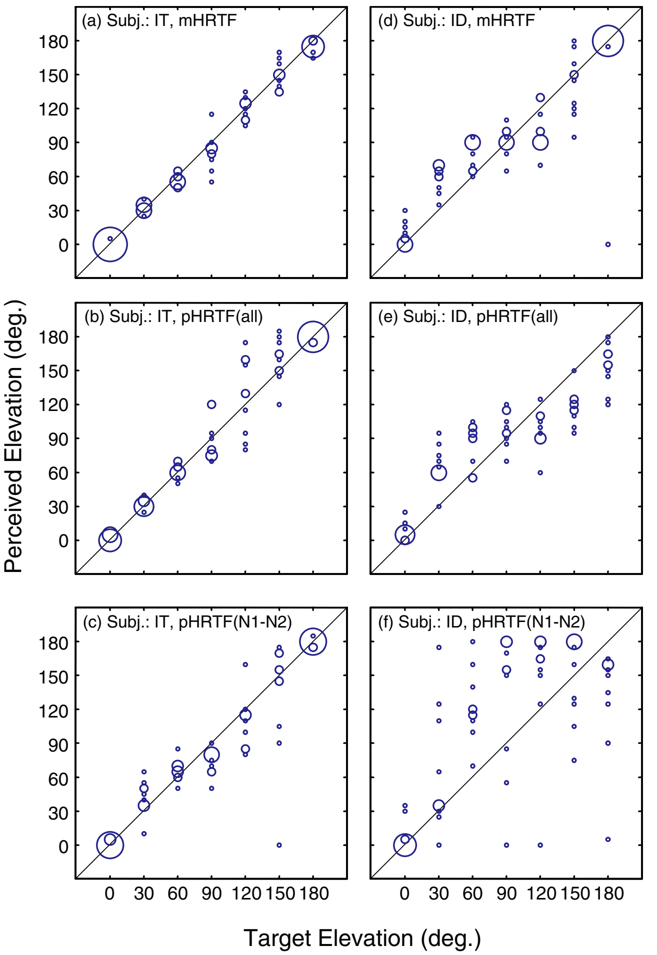

Fig. 6. Localization responses to mHRTF, pHRTF(all), and pHRTF(N1–N2).

the case of subject IT. However, in the case of subject ID, the responses to the stimuli tend to localize in a rear direction for the target elevations of 30, 60, 90, and 120°.

The localization error was calculated. The error is defined as the mean absolute deviation of the perceived elevation from the target elevation [14]. Statistical tests were performed to determine whether a difference in localization error between the mHRTF and the pHRTF is statistically significant or not. The statistical method used for the tests was the *t*-test. Fig. 7 and Table 1 show the localization error and the results of the *t*-test, respectively. There was no statistically significant difference between the pHRTF(all) and the mHRTF except for subject IT for the target elevation of 120°. Moreover, no statistically significant difference was observed between the pHRTF(N1–N2) and the mHRTF for all the target elevations, except for subject IT for the target elevation of 30° and subject ID for the target elevations of 60, 90, and 120°. This implies that N1 and N2 play an important role as spectral cues.

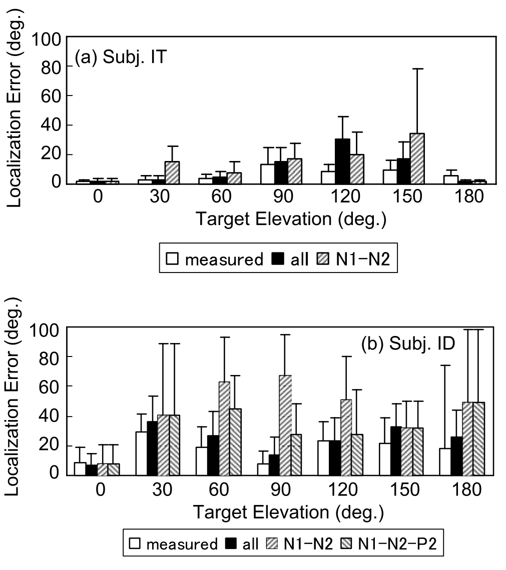

Fig. 7. Effects of HRTF condition on localization error for subjects IT and ID. Bars indicate standard deviations.

Table 1
Statistically significant difference in localization error between mHRTFs and pHRTFs for subjects IT and ID

Subject	pHRTF	Target elevation (°)						
		0	30	60	90	120	150	180
IT	All	–	–	–	–	**	–	–
	N1–N2	–	**	–	–	–	–	–
ID	All	–	–	–	–	–	–	–
	N1–N2	–	–	**	**	*	–	–
	N1–N2–P2	–	–	**	*	–	–	–

* $p < 0.05$.
** $p < 0.01$.

The pHRTF(all) of the target elevations of 60, 90, and 120° of subject ID consisted of only four peaks and notches, that is, P1, P2, N1, and N2. As mentioned above, for the target elevations of 60, 90, and 120°, statistically significant differences were observed between the pHRTF(N1–N2) and the mHRTF, but not between the pHRTF(all) and the mHRTF. Furthermore, statistically significant differences were observed between the pHRTF(N1–N2–P2) and the mHRTF for the target elevations of 60 and 90°. This implies that P1, which was not used in the tests, could contribute to the perception of elevation.

4. Localization test II

The results of localization test I show that N1 and N2 play an important role in the perception of elevation in the median plane, and that P1, the characteristics of which are independent of source elevation, could be a cue for the perception. The purpose of localization test II is to clarify the effect of P1 on median plane localization.

4.1. Method

The apparatus, source signal and target elevation were the same as those used in localization test I. However, test II was carried out in an anechoic chamber. The subject's own mHRTFs and pHRTFs in the upper median plane in 30° steps were used. The number of combinations of spectral peaks and notches of the pHRTF was eight; (1) N1, (2) N2, (3) P1, (4) N1–N2, (5) N1–P1, (6) N2–P1, (7) N1–N2–P1, and (8) all peaks and notches. The number of stimuli was 70. The subject was a female, 22 years of age, with a normal hearing sensitivity. She was not experienced in this type of localization test.

4.2. Results

Fig. 8 shows the distribution of the subject's responses. For the mHRTF, the subject perceived the elevation of a sound source accurately at all the target elevations. Similar results to localization test I were obtained for the pHRTF(all) and pHRTF recomposed of only one spectral peak or notch. In other words, the perceived elevation was as accurate as that for the mHRTF at all the target elevations for the pHRTF(all), and the variances of the responses were large for the pHRTF recomposed of only one spectral peak or notch at all the target elevations.

Fig. 9 shows the responses to the mHRTF, pHRTF(all), pHRTF(N1–N2), and pHRTF(N1–N2–P1) for seven target elevations. For the pHRTF(all), the responses distribute along a diagonal line, and this distribution is practically the same as that for the mHRTF. For the pHRTF(N1–N2), the responses distribute along a diagonal line for the target elevations of 120, 150, and 180°, but the responses for the target elevations of 0, 30, 60, and 90° shift to the rear. For the pHRTF(N1–N2–P1), the responses generally distribute along a diagonal line, except for the target elevation of 90°. The accuracy of elevation localization of the pHRTF(N1–N2–P1) is better than that of the pHRTF(N1–N2).

Fig. 10 and Table 2 show the localization error and the results of the *t*-test. There was no statistically significant difference between the pHRTF(all) and the mHRTF. Statistically significant differences were observed between the pHRTF(N1–N2) and the mHRTF except for the target elevations of 120 and 150°. Moreover, there was no significant difference between the pHRTF(N1–N2–P1) and the mHRTF, except for the target elevation of

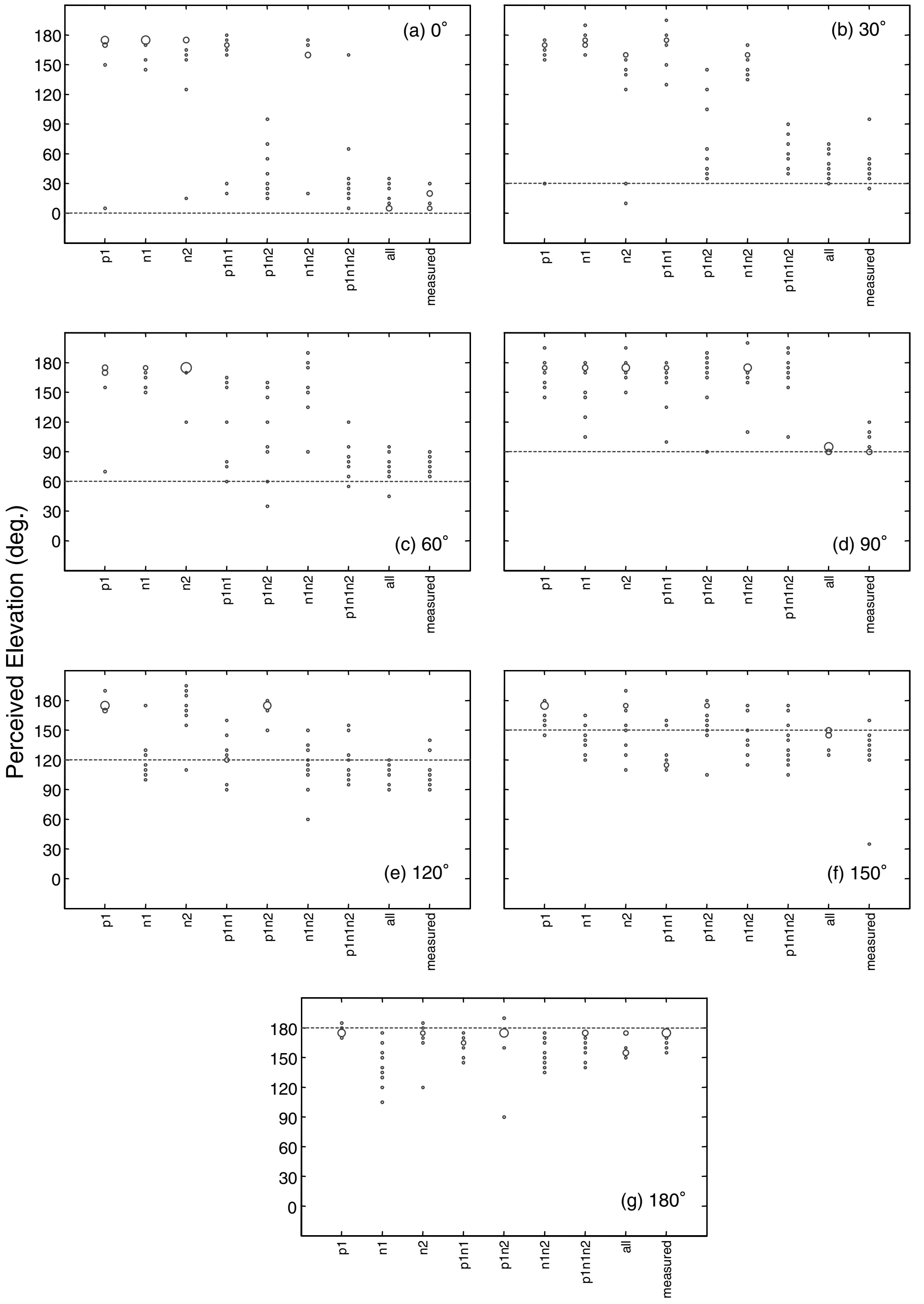

Fig. 8. Localization responses of subject MK for each target elevation.

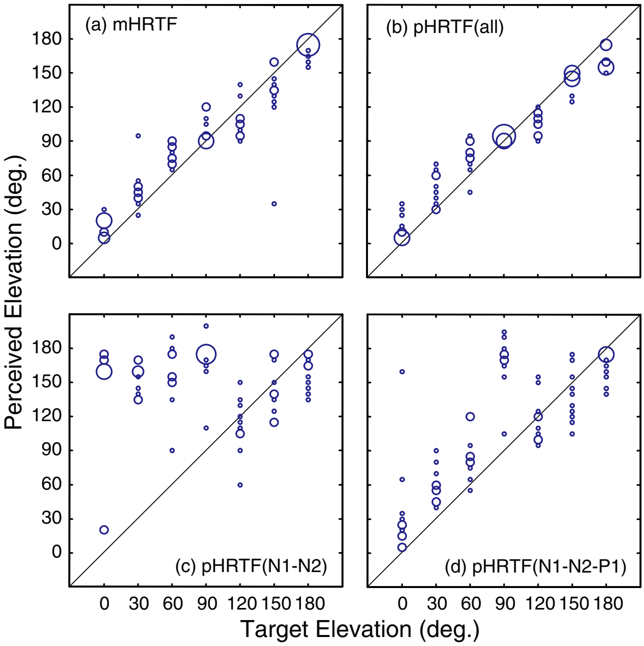

Fig. 9. Localization responses to mHRTF, pHRTF(all), pHRTF(N1–N2), and pHRTF(P1–N1–N2).

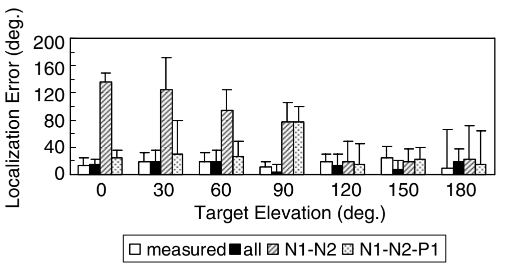

Fig. 10. Effects of HRTF condition on localization error for subject MK. Bars indicate standard deviations.

Table 2
Statistically significant difference in localization error between mHRTFs and pHRTFs for subject MK

Subject	pHRTF	Target elevation (°)						
		0	30	60	90	120	150	180
MK	All	–	–	–	–	–	–	–
	N1–N2	**	**	**	**	–	–	*
	N1–N2–P1	–	–	–	**	–	–	–

* $p < 0.05$.
** $p < 0.01$.

90°. The pHRTF(all) for 90° was recomposed of N1, N2, P1, P2 , and P3. There was no significant difference between the pHRTF(all) and the mHRTF for the target elevation of 90°. This implies that one of P2 and P3 or both of them is required in addition to N1, N2, and P1 to localize the elevation of 90° accurately.

5. Discussions

The reason why some spectral peaks and notches markedly contribute to the perception of elevation is discussed. Fig. 11 shows the spectral peaks and notches of the measured HRTFs of subject IT in the upper median plane in 30° steps. This figure shows that the parameters of N1 and N2, i.e., center frequency, level, and sharpness, change more remarkably than those of other spectral peaks and notches, as the elevation of a sound source changes in the upper median plane. It is supposed that the changes in the characteristics of these two spectral notches play an important role in the perception of elevation. This hypothesis is substantiated by other reported experiments. Hebrank and Wright [5] carried out experiments with a narrow-band noise and reported the following: front cues are a 1-octave notch having a lower cutoff frequency between 4 and 8 kHz (corresponding to N1) and increased energy above 13 kHz; a behind cue is a small peak between 10 and 12 kHz with a decrease in energy above and below the peak (corresponding to N1 and N2). The cues reported by Hebrank and Wright are consistent with our results. However, these cues were observed using a narrow-band noise. Listeners do not localize a sound image at a specific elevation through those cues when a wide-band noise is used. As mentioned in localization test I, neither a single spectral peak nor a single spectral notch provides sufficient information for localizing the elevation of a wide-band noise.

P2 corresponds to the above cue, a 1/4-octave peak between 7 and 9 kHz, reported by Hebrank and Wright. Blauert [3] also reported a similar result; that is, 8 kHz is a directional band for the above. For the target elevation of 90°, there was a statistically

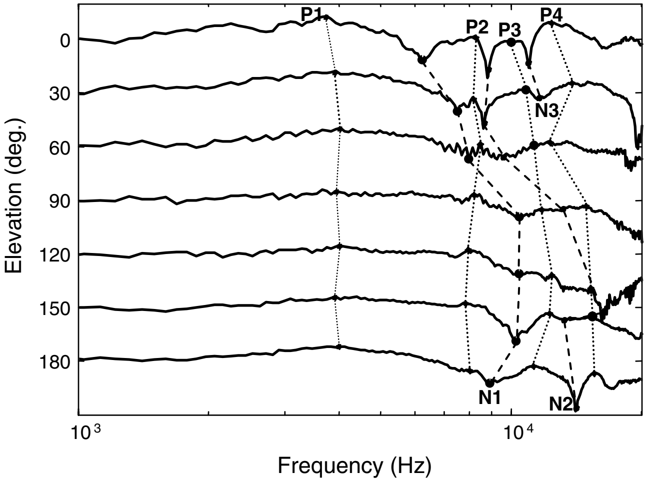

Fig. 11. Spectral peaks (dotted line) and notches (broken line) of measured HRTFs of subject IT in the upper median plane.

significant difference between the pHRTF(N1–N2) and the mHRTF in the responses of subject ID. In the responses of subject MK, significant differences were observed between the mHRTF and the pHRTF(N1–N2), and between the mHRTF and the pHRTF(N1–N2–P1) for the target elevation of 90°. These results infer that P2 plays an important role in the above localization.

On the other hand, the parameters of P1 do not depend on the source elevation. According to Shaw and Teranishi [2], the meatus-blocked response shows a broad primary resonance, which contributes almost 10 dB of gain over the 4–6 kHz band, and the response in this region is controlled by a ‘‘depth’’ resonance of the concha. Therefore, the contribution of P1 to the perception of elevation cannot be explained in the same manner as those of N1 and N2. It could be considered that the hearing system of a human being utilizes P1 as the reference information to analyze N1 and N2 in the ear-input signals. Some previous studies support this hypothesis. Iida and Morimoto [23] reported that the hearing system determines the elevation of a sound source using only the spectrum information of the ear input-signals, regardless of *a priori* knowledge on the source signal. The spectrum analysis is easier if a frequency band that has common characteristics independent of incident sound elevation exists. A similar consideration was introduced by Asano et al. [16]. They proposed the following hypothesis: The boundary of the frequency areas that separate the front-rear judgment cues in the low-frequency range and elevation angle judgment cues in the high-frequency range exists at around 2–5 kHz, and the perceived elevation angle is related to the ratio of the power in the area above that boundary to that of the area below.

An individual difference in the contribution of P1 to the perception of elevation was observed in the localization tests. This individual difference seemed to be caused by the subject’s ability of localization, for instance, the degree of learning of the spectral cues. However, further investigation must be performed to confirm the consideration.

6. Conclusions

A method of HRTF modeling based on spectral cues for vertical localization was investigated. Authors proposed a parametric HRTF model for simulating vertical sound localization. The parametric HRTF is recomposed only of the spectral peaks and notches extracted from the measured HRTF, and the characteristics of the spectral peaks and notches are expressed parametrically with center frequency, level, and sharpness. Localization tests were carried out in the upper median plane using the subjects’ own measured HRTFs and the parametric HRTFs with various combinations of spectral peaks and notches. The results show that (1) perceived elevation for the parametric HRTF recomposed of all the spectral peaks and notches is as accurate as that for the measured HRTF; (2) some spectral peaks and notches play an important role in determining the perceived elevation, whereas some peaks and notches do not; (3) the parametric HRTF recomposed of the first and second notches (N1 and N2) and the first peak (P1) provides almost the same accuracy of elevation perception as the measured HRTFs.

Observations of the spectral peaks and notches of the HRTFs in the upper median plane indicate that (1) the center frequency, level, and sharpness of N1 and N2 change remarkably as the source elevation changes; (2) whereas, P1 does not depend on the source elevation.

From these results, it is concluded that (1) N1 and N2 can be regarded as spectral cues; (2) the hearing system of a human being could utilize P1 as the reference information to analyze N1 and N2 in ear-input signals.

References

[1] Roffler K, Butler A. Factors that influence the localization of sound in the vertical plane. J Acoust Soc Am 1968;43:1255–9.
[2] Shaw EAG, Teranishi R. Sound pressure generated in an external-ear replica and real human ears by a nearby point source. J Acoust Soc Am 1968;44:240–9.
[3] Blauert J. Sound localization in the median plane. Acustica 1969–1970;22:205–13.
[4] Gardner B, Gardner S. Problem of localization in the median plane: effect of pinna cavity occlusion. J Acoust Soc Am 1973;53:400–8.
[5] Hebrank J, Wright D. Spectral cues used in the localization of sound sources on the median plane. J Acoust Soc Am 1974;56:1829–34.
[6] Butler A, Belendiuk K. Spectral cues utilizes in the localization of sound in the median sagittal plane. J Acoust Soc Am 1977;61:1264–9.
[7] Mehrgardt S, Mellert V. Transformation characteristics of the external human ear. J Acoust Soc Am 1977;61:1567–76.
[8] Watkins AJ. Psychoacoustic aspects of synthesized vertical locale cues. J Acoust Soc Am 1978;63:1152–65.
[9] Morimoto M, Aokata H. Localization cues of sound sources in the upper hemisphere. J Acoust Soc Jpn (E) 1984;5(3):165–73.
[10] Middlebrooks JC. Narrow-band sound localization related to external ear acoustics. J Acoust Soc Am 1992;92(5):2607–24.
[11] Iida K, Yairi M, Morimoto M. Role of pinna cavities in median plane localization. In: Proceedings of 16th International Congress on Acoustics, 1998. 845–46.
[12] Moore BCJ, Oldfield R, Dooley GJ. Detection and discrimination of peaks and notches at 1 and 8 kHz. J Acoust Soc Am 1989;85(2):820–36.
[13] Raykar VC, Duraiswami R, Yegnanarayana B. Extracting the frequencies of the pinna spectral notches in measured head related impulse responses. J Acoust Soc Am 2005;118(1):364–74.
[14] Morimoto M, Ando Y. On the simulation of sound localization. J Acoust Soc Jpn (E) 1980;1(3):167–74.
[15] Kendall, GS, Rodgers, CAP. The simulation of three-dimensional localization cues for headphone listening. In: Proceedings of the 1981 International Computer Music Conference, 1981. 225–43.
[16] Asano F, Suzuki Y, Sone T. Role of spectral cues in median plane localization. J Acoust Soc Am 1990;88(1):159–68.
[17] Blommer MA, Wakefield GH. Pole-zero approximations for head-related transfer functions using a logarithmic error criterion. IEEE T Speech Audi P 1997;5:278–87.
[18] Haneda Y, Makino S, Kaneda Y, Kitawaki N. Common-acoustical-pole and zero modeling of head-related transfer functions. IEEE T Speech Audi P 1999;7:188–96.
[19] Durant EA, Wakefield GH. Efficient model fitting using a genetic algorithm: Pole-zero approximations of HRTFs. IEEE T Speech Audi P 2002;10:18–27.
[20] Kulkarni A, Colburn HS. Infinite-impulse-response models of the head-related transfer function. J Acoust Soc Am 2004;115(4):1714–28.
[21] Morimoto M, Iida K, Itoh M. Upper hemisphere sound localization using head-related transfer functions in the median plane and interaural differences. Acoustical Sci Technol 2003;24(5):267–75.
[22] Hammershøi D, Møller H. Sound transmission to and within the human ear canal. J Acoust Soc Am 1996;100(1):408–27.
[23] Iida K, Morimoto M. A priori knowledge of the sound source spectrum in median plane localization. J Acoust Soc Am 1999;105(2 Pt.2):1391.