Applied Acoustics **38** (1993) 291–301

Relation between Auditory Source Width in Various Sound Fields and Degree of Interaural Cross-Correlation

M. Morimoto

Environmental Acoustics Laboratory, Faculty of Engineering,
Kobe University, Rokko, Nada, Kobe 657, Japan

K. Iida

Environmental Acoustics Laboratory, Faculty of Engineering,
Kobe University, and Matsushita Communication Industrial Co., Ltd.
Saedo, Midori, Yokohama 226, Japan

&

Y. Furue

Faculty of Engineering, Kyoto University, Yoshida-honmachi,
Sakyo, Kyoto 606, Japan

(Received 10 December 1991; revised version received 9 March 1992; accepted 12 March 1992)

ABSTRACT

The purpose of this paper is to investigate whether or not the degree of interaural cross-correlation can be widely applied as a physical factor to estimate auditory source width (ASW) perceived in any sound field. Results of two hearing tests infer the following. ASW perceived in different sound fields with the same degree of interaural cross-correlation are equal to each other, regardless of number and arriving direction of reflection. But, ASW perceived in a sound field where a direct sound arrives from 30°, 60° and 90° in azimuth is narrower than ASW in a sound field where a direct sound arrives from the front direction.

Applied Acoustics 0003-682X/93/$06.00

1 INTRODUCTION

Listeners perceive three attributes of an auditory event in a sound field. They are the temporal (reverberance, rhythm, durability, etc.), the spatial (direction, distance, broadening, etc.) and the qualitative (loudness, timbre, pitch, etc.) attributes. Among them, the spatial attribute, especially broadening, is one of the most important subjects in designing, controlling and simulating the sound field.

It has been indicated that broadening consists of 'auditory source width (ASW)' and 'feeling of envelopment'.[1,2] In these papers Morimoto and Maekawa defined 'ASW' as the width of an auditory event perceived temporally and spatially to be fused with the auditory event of a direct sound and 'feeling of envelopment' as the fullness of an auditory event around a listener, excluding an auditory event relating to ASW.

In the past, ASW has been investigated in terms of spatial impression, auditory spaciousness, and so on. The degree of interaural cross-correlation[3] is well known as a physical factor for ASW. Chernyak and Dubrovsky,[4] Anazawa *et al.*,[5] and Kurozumi and Ohgushi[6] investigated directly the relation between ASW and the degree of interaural cross-correlation. All of their results indicated that ASW is negatively correlated with the degree of interaural cross-correlation.

Meanwhile, Barron[7] and Barron and Marshall[8] reported the lateral energy fraction as a physical factor for ASW and indicated that ASW is positively correlated with the lateral energy fraction. They showed that the lateral energy fraction is negatively correlated with the degree of interaural cross-correlation under certain conditions.

All stimuli in the past experiments, however, were presented to the subjects through headphones or loudspeakers arranged in symmetry between the left and the right. Therefore, it is not yet clear whether or not those physical factors are effective for estimating ASW, when reflections arrive from arbitrary directions in an enclosure like a concert hall and in a sound field produced by multi-channel loudspeakers.

The purpose of this paper is to investigate whether the degree of interaural cross-correlation can be widely applied as a physical factor to estimate ASW or not, regardless of arriving direction of reflections which is limited to a maximum of four in the experiments.

In this paper two experiments were performed. In the first experiment, a direct sound arrives from the front and in the second experiment, a direct sound arrives from another direction. Those experiments were carried out by using the method of adjustment by a subject himself, that is, a subject equated the variable comparison field and the fixed test field with regard to ASW by controlling the degree of interaural cross-correlation of the variable comparison field by himself.

2 EXPERIMENT I: A CASE OF A DIRECT SOUND ARRIVING FROM THE FRONT

2.1 Experimental conditions

2.1.1 Music motif

The motif used in the experiment was a 47 s section of the fourth movement of Mozart's *Jupiter Symphony* (No. 41), bars 94–151, recorded by the English Chamber Orchestra in the Building Research Station anechoic chamber, which was the same as the motif used by Barron[7] and Barron and Marshall.[8]

2.1.2 Apparatus

Figure 1 is a block diagram for the experiment. Thirteen cylindrical loudspeakers (diameter 108 mm, length 350 mm) for the fixed test field were arranged at a horizontal angle of 0°, ±30°, ±45°, ±60°, ±90°, ±120°, ±150° from the median plane at 1·5 m distance. The other three loudspeakers for the variable comparison field were placed on the loudspeakers for the fixed test field at a horizontal angle of 0° and ±45°. In total, 16 loudspeakers were used in the experiment. In both fields, the loudspeaker at 0° radiated a direct sound and the other loudspeakers radiated reflections. The frequency characteristics of all loudspeakers were equalised within ±2·5 dB in the frequency range from 100 Hz to 10 kHz by a digital frequency equalizer (Technics DSE-10).

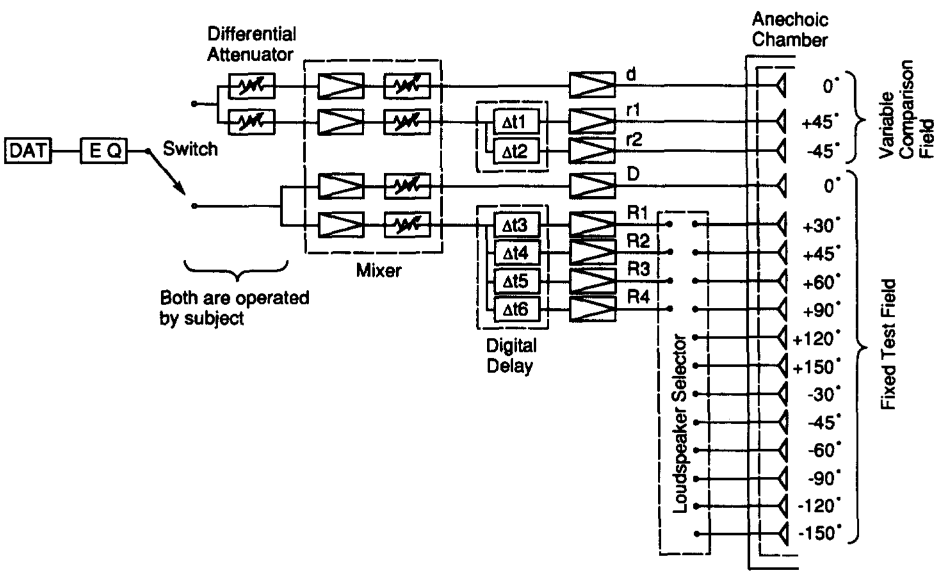

Fig. 1. Block diagram for experiment I. *d*, *r*1, and *r*2 are a direct sound and reflections of a variable comparison field respectively (see Fig. 2). *D* and *R*1–*R*4 are a direct sound and reflections of fixed test fields respectively (see Fig. 3). Δ*t*1–Δ*t*6 are time delays of reflections (*r*1, *r*2 and *R*1–*R*4) after a direct sound.

The music signal reproduced by a digital audio tape recorder (SONY DTC-500ES) passed through a digital equaliser and was divided into two systems with a switch. One system produced the variable comparison field and another system produced the fixed test field. The system for the variable comparison field was divided into a direct sound channel and a reflection channel with a differential attenuator. The differential attenuator has one input terminal and two output terminals, and allowed the relative level of the direct sound and the reflections to be varied with an incoherent sum of the two levels kept constant. The system for the fixed test field was divided into a direct sound channel and a reflection channel with an audio mixer. Furthermore, the reflection channels in both systems provided two or four reflections with a digital delay (Yamaha 2600). A direct sound and reflections were fed to amplifiers and radiated from the loudspeakers in both fields.

2.1.3 Kind of structure of reflections

The parameter, the degree of interaural cross-correlation of the fixed test field, was set to 0·6 or 0·8. The degree of interaural cross-correlation was controlled by changing the relative level of the reflections to the direct sound and measured by using a KEMAR dummy head without an artificial ear simulator (BK DB-100) and a microphone amplifier with flat frequency response. This measuring method of the degree of interaural cross-correlation is suitable to estimate ASW for the music motif used in this experiment.[9]

Figure 2 is the structure of reflections of the variable comparison field. The field consists of a direct sound and two reflections. The direct sound was radiated from the front of a subject and the reflections were radiated from horizontal angles of $\pm 45°$. Reflection delays were 25 and 45 ms. The sound pressure levels of reflections were equal to each other. The relative level of the reflections to the direct sound was changed with a differential attenuator controlled by the subject himself.

Figure 3 shows the structures of reflections of the fixed test fields. The field

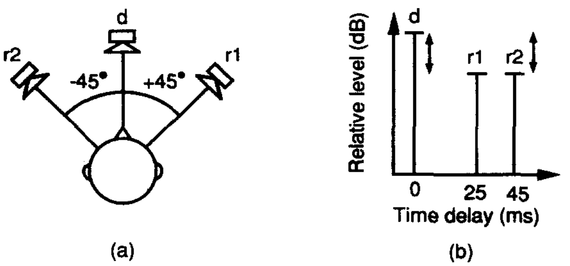

Fig. 2. Structure of (a) reflections and (b) impulse response of a variable comparison field in experiment I. *d* is a direct sound and *r*1 and *r*2 are reflections.

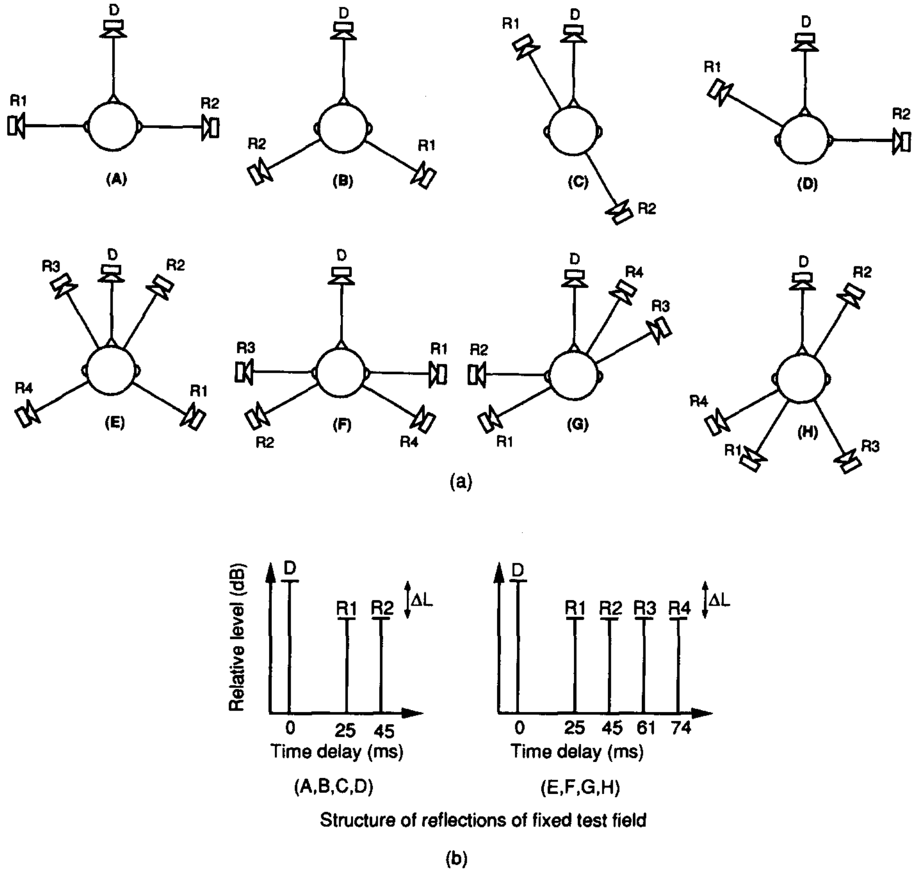

Fig. 3. Kinds of structure of (a) reflections and (b) impulse response of fixed test fields in experiment I. D is a direct sound and $R1$–$R4$ are reflections. ΔL is SPL relative to a direct sound.

consists of a direct sound and two or four reflections. Eight kinds (A–H) of the combination of arriving direction of reflections were selected considering the front–back and the left–right symmetry. Reflection delays were 25, 45, 61 and 74 ms. The sound pressure levels of reflections were equal to each other. The relative level of the reflections to the direct sound were fixed at the level where the degree of interaural cross-correlation was kept to be 0·6 or 0·8. Furthermore, the same structure of reflections as the variable comparison field shown in Fig. 2 was added as a fixed test field T for reference.

The total sound pressure level of all fields measured at the left ear of a KEMAR dummy head without an artificial ear simulator (BK DB-100) were constant at 70 dB(A) slow peak.

2.1.4 Procedure

The subject was tested, while seated, with head fixed in a partially darkened anechoic chamber.

He could switch at will between the fixed test field and the variable comparison field, and control the degree of interaural cross-correlation of the variable comparison field in the range from 0·33 to 0·97 with the differential attenuator. The task of the subject was to equate the variable comparison field and one of nine kinds of the fixed test fields with regard to ASW. The music motif of 47 s length was presented repetitively until the task of the subject was finished.

The order of presentation of nine fixed test fields was different for each subject. Each subject was tested six times for each fixed test field.

2.1.5 Subject

Five male students (23–24 years) with normal hearing sensitivity acted as subjects in the experiment. They had no previous experience in psycho-acoustical experiments.

2.2 Experimental results and discussions

The subjects perceived no echo in any of the sound fields. The first responses of each subject to each fixed test field were regarded as a practice trial and they were excluded from the results.

Figure 4 shows the 95% confidence interval of the degree of interaural cross-correlation of the variable comparison field, ASW for which is judged to be equal to ASW for each of nine fixed test fields. The dashed dotted line is the set degree of the interaural cross-correlation of the fixed test field. The two dotted lines indicate the just noticeable difference (jnd) of the degree of interaural cross-correlation with regard to ASW.[10] The jnd was measured by the constant method for the sound field which consisted of the same structure of reflections as the comparison field in this experiment, using the same music motif as that used in this experiment.

First, consider the results for the degree of interaural cross-correlation of 0·8. The 95% confidence intervals for the test fields overlap 0·8 except the test fields *H* and *T*. The 95% confidence interval for the test field *T* with the same structure of reflections as the comparison field overlaps the intervals for all test fields except the test field *E*. The 95% confidence intervals for all test fields overlap each other, except that the 95% confidence interval for the test field *E* does not overlap the intervals for the test fields of *H* and *T*.

Next, consider the results for the degree of interaural cross-correlation of 0·6. The 95% confidence interval for the test field *T* with the same structure of reflections as the comparison field overlaps the intervals for all test fields

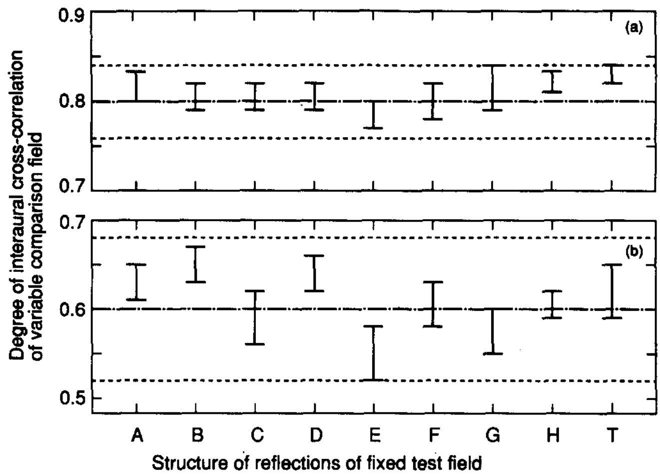

Fig. 4. 95% confidence interval of degree of interaural cross-correlation of a variable comparison field, auditory source width for which is equal to ASW for fixed test fields in experiment I. Degree of interaural cross-correlation of fixed test fields is (a) 0·8 and (b) 0·6. (–·–·–) Interaural cross-correlation of fixed test field. The two dotted lines indicate jnd of the degree of interaural cross-correlation with regard to ASW measured for the sound field with the same structure of reflections as a variable comparison field.

except the test field *E* as well as the results for the degree of interaural cross-correlation of 0·8. But, the 95% confidence intervals for which overlap 0·6 are only those of the four test fields of *C*, *F*, *H* and *T*. The 95% confidence intervals for all test fields do not always overlap each other.

Here, consider the 95% confidence interval for the test field *T*. The interval essentially should overlap 0·8 and 0·6 centring around 0·8 and 0·6, respectively, since the field *T* consists of the same structure of reflections as the comparison field. The interval, however, is 0·82–0·84 and 0·59–0·65, respectively. The interval for 0·8 does not overlap 0·8 and the interval for 0·6 shifts to higher than 0·6. Namely, the judgements by subjects were considered to be biased. To use the method of adjustment by a subject in these experiments, is considered to be the cause.

Therefore, it is easy to understand that the bias for 0·6 is larger than the bias for 0·8, since the jnd for 0·6 is larger than the jnd for 0·8. The 95% confidence intervals for all test fields are, however, within the jnd of the degree of interaural cross-correlation with regard to ASW which was obtained for the sound field which consisted of the same structure of reflections as the comparison field in this experiment, and by using the same music motif.

From these discussions, it seems to suggest that ASW produced by nine fixed test fields (A–H and T) with different structures of reflections are equal to each other, if the degree of interaural cross-correlation of those fields are equal to each other.

3 EXPERIMENT II: A CASE OF A DIRECT SOUND ARRIVING FROM THE OTHER DIRECTIONS

3.1 Experimental conditions

3.1.1 Music motif
The same music motif as in experiment I was used.

3.1.2 Apparatus
The same apparatus as in experiment I was used, except for the number and the directions of loudspeakers.

3.1.3 Kind of arriving direction of a direct sound
The parameter, the degree of interaural cross-correlation of the fixed test field, was set 0·6 and 0·8.

The structure of reflections of the variable comparison field is the same as that used in experiment I (see Fig. 2). The field consists of a direct sound and two reflections. The direct sound was radiated from the front of a subject and the reflections were radiated from horizontal angles of $\pm 45°$. If a direct sound of the variable comparison field does not arrive from the front, it is difficult for a subject to judge, since the direction of the sound image as well as ASW changes as the relative level of reflections to the direct sound changes.

Figure 5 shows the structures of reflections of the fixed test fields. The field consists of a direct sound and two reflections. Three kinds (A–C) of the arriving direction of a direct sound were selected. They were 30°, 60° and 90°. Reflection delays were 25 and 45 ms. The sound pressure levels of reflections

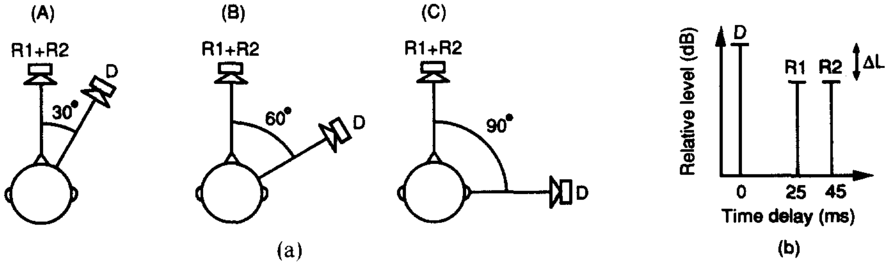

Fig. 5. Kinds of structure of (a) a direct sound and reflections and (b) impulse response of fixed test fields in experiment II. D is a direct sound and $R1$–$R2$ are reflections. ΔL is SPL relative to a direct sound.

were equal to each other. The relative level of the reflections to the direct sound were fixed at the level where the degree of interaural cross-correlation was kept to be 0·6 or 0·8. But, the fixed test field where the direct sound arrived from 60° and the degree of interaural cross-correlation of which was 0·8 could not be technically produced. The total sound pressure level of all fields measured at the position corresponding to the centre of the KEMAR dummy head were constant at 67 dB(A) slow peak.

3.1.4 Procedure

Each subject was tested 10 times (rather than six) for each fixed test field because the subject's task in this experiment was more difficult than the experiment I. The other procedure was the same as the experiment I.

3.1.5 Subject

Five male students acted as subjects. Three of them were also subjects in experiment I.

3.2 Experimental results and discussions

The subjects perceived no echo for all sound fields. The first five responses of each subject to each fixed test field were regarded as a practice trial and they

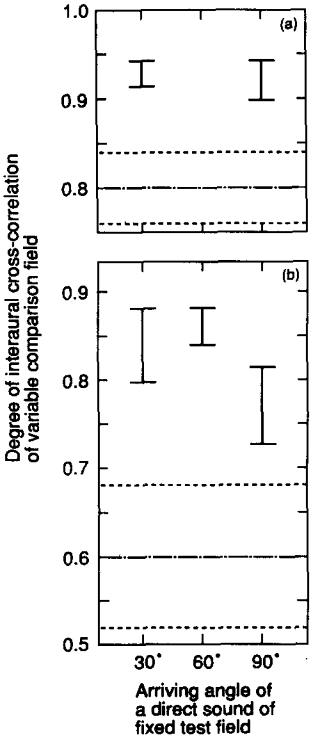

Fig. 6. 95% confidence interval of degree of interaural cross-correlation of a variable comparison field, auditory source width for which is equal to ASW for fixed test fields in experiment II. Degree of interaural cross-correlation of fixed test fields is (a) 0·8 and (b) 0·6. (–·–·–) Interaural cross-correlation of fixed test field. The two dotted lines indicate jnd of the degree of interaural cross-correlation with regard to ASW measured for the sound field with the same structure of reflections as a variable comparison field.

were excluded from the results. Figure 6 shows the 95% confidence interval of the degree of interaural cross-correlation of the variable comparison field, ASW for which is judged to be equal to ASW for each of the five fixed test fields. The dashed dotted line is the set degree of the interaural cross-correlation of the fixed test field. The two dotted lines indicate the jnd of the degree of interaural cross-correlation with regard to ASW as shown in Fig. 4.

The 95% confidence interval for all test fields significantly shifts to higher than the set degree of interaural cross-correlation of the test field, 0·6 and 0·8, respectively. Furthermore, the 95% confidence intervals of all test fields and jnd do not overlap each other at all.

Namely, it seems to suggest that ASW perceived in a sound field where a direct sound arrives from any direction excluding the front is narrower than ASW in a sound field where a direct sound arrives from the front, even if their degree of the interaural cross-correlation are equal to each other, though these results include such a bias caused by the experimental method as in experiment I.

4 CONCLUSIONS

Two experiments were performed to investigate the relation between auditory source width (ASW) produced by different structures of reflections and the degree of interaural cross-correlation. The results of two experiments infer the following: although definite conclusions cannot be drawn because of the bias of the subject's judgement caused by the method of adjustment by a subject.

(1) ASW perceived in different sound fields with the same degree of interaural cross-correlation are equal to each other, regardless of a structure of reflections (number and arriving direction of reflection).

(2) But, ASW perceived in a sound field where a direct sound arrives from 30°, 60° and 90° in azimuth is narrower than ASW in a sound field where the direct sound arrives from the front, even if their degree of the interaural cross-correlation are equal to each other.

ACKNOWLEDGEMENTS

The authors wish to thank Prof. Z. Maekawa (presently, Emeritus Professor of Kobe University) for his encouragement and Prof. T. Gotoh of Shizuoka University for his helpful advice. Thanks also to Mr H. Kitatani, Mr H. Ohtsuka and Mr A. Kintsuji for their cooperation in the experiments.

REFERENCES

1. Morimoto, M. & Maekawa, Z., Auditory spaciousness and envelopment. In *Proceedings of the 13th International Congress on Acoustics*, Vol. 2, Belgrade, 1989, pp. 215–18.
2. Morimoto, M., Fujimori, H. & Maekawa, Z., Discrimination between auditory source width and envelopment. *J. Acoust. Soc. Jpn*, **6** (1990) 449–57 (in Japanese).
3. Damaske, P. & Ando, Y., Interaural cross-correlation for multichannel loudspeaker reproduction. *Acustica*, **27** (1972) 232–8.
4. Chernyak, R. I. & Dubrovsky, N. A., Pattern of the noise images and the binaural summation of loudness for the different interaural correlation of noise. In *Proceedings of the 6th International Congress on Acoustics*, Tokyo, 1968, pp. 215–18.
5. Anazawa, T., Yanagawa, H. & Ito, T., On correlation coefficients of both ears and feeling of wideness. *Trans. Tech. Comm. Acoust. Soc. Jpn*, (1970) EA70-13 (in Japanese).
6. Kurozumi, K. & Ohgushi, K., The relationship between the cross-correlation coefficient of two-channel acoustic signals and sound image quality. *J. Acoust. Soc. Amer.*, **74** (1983) 1726–33.
7. Barron, M., The subjective effects of first reflections in concert halls—The need for lateral reflections. *JSV*, **15** (1971) 475–94.
8. Barron, M. & Marshall, A. H., Spatial impression due to the early reflections in concert halls: The deviation of a physical measure. *JSV*, **77** (1981) 221–32.
9. Morimoto, M., Fujimori, H. & Maekawa, Z., A consideration on measurement of interaural cross correlation coefficient as a measure of auditory source width. In *Proceedings of the Meeting of Acoustic Society of Japan*, Vol. 2, Nagoya, 1990, pp. 627–28, (in Japanese).
10. Kashiwa, M., Just noticeable difference of interaural cross-correlation with regard to auditory source width for music motif. Graduation thesis, Kobe University, Japan, 1991 (in Japanese).