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A practical evaluation method of auditory source width in concert halls

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This paper investigates how to measure the degree of interaural cross correlation (ICC) as a physical measure of auditory source width (ASW), the just noticeable difference (jnd) of ASW and the estimation equation of ASW in degree for a music motif as a practical evaluation method of ASW in concert halls. Some physical measurements and psychological experiments show the following results. (1) ICC measured without A-weighting using a dummy head without ear simulators agree with spatial impression measured by Barron and Marshall which corresponds to ASW. It is termed DICC, in distinction from IACC measured with A-weighting. (2) Weber's law is applicable to the perception of ASW. The measured *jnd* becomes smaller as DICC becomes higher, and the Weber's ratio, $\Delta DICC/(1-DICC)$ is almost constant in the range from 0.2 to 0.3. (3) The equation and the chart to estimate ASW in degree are obtained as functions of DICC and the binaural summation of sound pressure level (BSPL). An increase of DICC by 0.1 causes a decrease of ASW by about 4° and an increase of BSPL by 1 dB causes an increase of ASW by about 1.6°. A decrease of DICC by 0.1 is equivalent to an increase of BSPL by 2.6 dB in ASW.

Keywords: Broadening of sound image, Auditory source width, Interaural cross correction, Concert hall

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1. INTRODUCTION

Broadening is an important characteristic of a sound image for psychological evaluations of sound fields. Auditory source width (ASW) is one of two characteristics that compose broadening of a sound image.[1] The lateral energy fraction L_f[2] and the degree of interaural cross correlation (ICC) are well-known as physical measures for ASW. The criteria[2] and the measurement method[3] of L_f have been discussed for its practical use. As a result, L_f is already put to practical use. But, any knowledge necessary for practical use of ICC has not yet been clarified except that ICC has a negative correlation with ASW.

ICC is generally defined as follows;

$$\mathrm{ICC}=|\Phi_{\mathrm{lr}}(\tau)|_{\max} \tag{1}$$

where $|\tau|\leq$maximum interaural time difference. The interaural cross correlation function $\Phi_{\mathrm{lr}}(\tau)$ is generally defined as:

$$\Phi_{\mathrm{lr}}(\tau)=\lim_{T\to\infty}\frac{\dfrac{1}{2T}\displaystyle\int_{-T}^{+T}p_{\mathrm{l}}(t)p_{\mathrm{r}}(t-\tau)dt}{\dfrac{1}{2T}\sqrt{\displaystyle\int_{-T}^{+T}p_{\mathrm{l}}^2(t)dt\int_{-T}^{+T}p_{\mathrm{r}}^2(t)dt}} \tag{2}$$

where $p_{\mathrm{l}}(t)$ and $p_{\mathrm{r}}(t)$ are the input signals to the left and right ears, respectively and described as follows.

$$p_{\mathrm{l}}(t)=s(t)*r(t)*h_{\mathrm{l}}(t)$$
$$p_{\mathrm{r}}(t)=s(t)*r(t)*h_{\mathrm{r}}(t) \tag{3}$$

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where $s(t)$ is a source signal, $r(t)$ is a room impulse response, $h(t)$ is a head-related impulse response and an asterisk indicates convolution.

As shown in Eqs. (1), (2) and (3), ICC depends not only on a room impulse response $r(t)$, but also on a source signal $s(t)$ and a head-related impulse response $h(t)$. Therefore, it is impossible to discuss the usefulness of a single number physical measure without limiting source signals, so long as all cues for perception of ASW do not become clear, though one of authors is investigating the estimation method of ASW for any source signal.[4] At present, however, even for a limited source signal, there is no practically useful physical measure and criterion based on ICC to evaluate ASW for acoustical designs of concert halls. Most of present data is obtained for narrow band source signals such as 1/1 and 1/3 oct. band noises.[5,6]

In this paper ASW for a music motif is discussed, since this is the appropriate signal for a concert hall. The following three topics relevant to the practical acoustical design of concert halls are investigated: (1) the measuring method of ICC as a physical measure which is the most useful for ASW for a music motif, (2) the just noticeable difference (jnd) of ASW for a music motif, and (3) the absolute value of ASW in degree for a music motif as functions of ICC and the sound pressure level. However, there are a limitless number of possible music samples. Therefore, which music motif should be selected as a standard one is an important problem to make the results more general. In this paper, Mozart's Symphony No. 41 "Jupiter" is used as a standard music motif, since it is an orchestra music composed of various musical instruments and it was used in Barrow and Marshall's experiment from which L_f[2] was derived.

2. MEASURING METHOD OF THE DEGREE OF INTERAURAL CROSS CORRELATION AS A PHYSICAL MEASURE FOR ASW

As mentioned above, ICC depends on the head-related impulse responses $h(t)$. It can be considered as the acoustical characteristics of a receiving system in ordinary acoustical measurements. Therefore, the measured value of ICC depends on how $h(t)$ is treated. For instance, IACC which is a physical measure based on ICC is the value measured using a dummy head without artificial ear simulators and with A-weighting.[7] But it is not clear whether IACC is the most adequate to evaluate ASW for a music motif, or not. In this paper, three kinds of measuring methods of ICC as a physical measure for ASW are investigated considering $h(t)$.

2.1 Method

The results of the experiment on spatial impression by Barron and Marshall[2] were utilized in this investigation. From their experimental conditions, spatial impression can be regarded as being the same characteristic of a sound image as ASW defined by Morimoto.[1]

In their experiment, Mozart's "Jupiter" Symphony No. 41 (4th movement, 47 s long, bars 94–151) was used as a music motif. The sound field consisted of a direct sound placed in front and two lateral reflections placed symmetrically relative to the subject. Figure 1 shows the impulse responses of two sound fields used in their experiment. The sound pressure levels of two reflections were equal and their delays were constant at 40 and 41 ms. For a variable comparison field, the relative sound pressure levels of reflections to a direct sound were changed with the incoherent sum of the levels of a direct sound and reflections kept constant but their directions were fixed at $\pm\alpha=90°$. For a fixed test field, the sound pressure levels of reflections were fixed but their directions were changed. ASW produced by pairs of reflections from different directions were compared. Self-testing comparison experiments were conducted with a fixed test field containing a pair of reflections at azimuth $\pm\alpha°$ and a variable comparison field with reflections at $\pm\alpha=90°$. The subject was asked to equate two sound fields with regard to ASW by controlling the ratio of

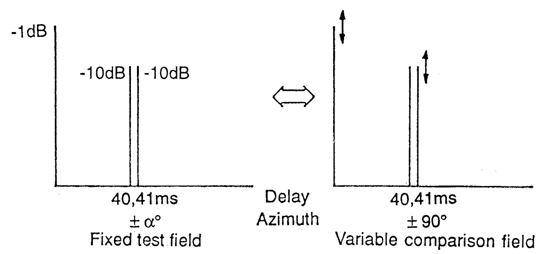

Fig. 1 Impulse responses of sound fields for comparison in the degree of spatial impression with reflection azimuth experiment (after Barron and Marshall[2]).

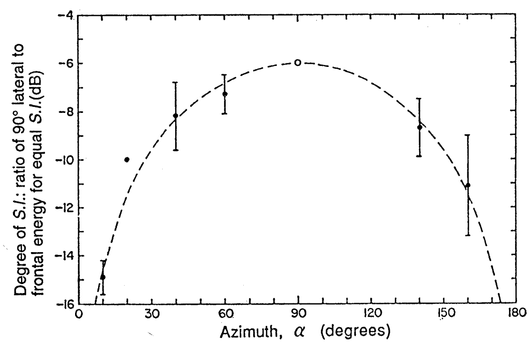

Fig. 2 Degree of spatial impression for pairs of reflections as the reflection angle of azimuth is varied. Filled circle, mean; bar, 95% confidence limit of the mean of experimental results; broken line, predicted results for sine relationship (after Barron and Marshall[2]).

90° lateral reflection energy to the direct (or frontal) energy of a variable comparison field. The results are plotted in Fig. 2; the ordinate is the ratio of 90° lateral reflection energy to the direct (or frontal) energy of a variable comparison field expressed in dB for equal ASW; the $\pm\alpha=90°$ value is by definition and not experimental.

The measurements of ICC were conducted using the same sound field as Barron and Marshall's. The distance between the center of a dummy head and loudspeakers was 1.5 m. The frequency characteristics of the loudspeakers were flat within ± 3 dB in the range from 100 Hz to 10 kHz. The KEMAR dummy head[8] was used for measurements.

ICC of variable comparison fields and fixed test fields were measured under three conditions of $h(t)$; Method A, a dummy head with artificial ear simulators (B & K Type DB-100) and without A-weighting; Method B, a dummy head without artificial ear simulators and with A-weighting; Method C, a dummy head without artificial ear simulators and without A-weighting. ICC measured by Method B is so-called IACC.

At first, ICC of variable comparison fields were measured. As in the right figure in Fig. 1, the directions of lateral loudspeakers were fixed at $\pm\alpha=90°$. The ratio of lateral to frontal energy was set at the values plotted by filled circles and also at the both ends of 95% confidence limit bars in Fig. 2. Next, ICC of fixed test fields were measured. As in the left figure in Fig. 1, the directions of lateral reflections were changed at $\pm\alpha=10°$, 20°, 40°, 60°, 90°, 140° and 160°. The relative sound pressure level of each reflection to a direct sound was fixed at -9 dB. ICC for $\pm\alpha=90°$ was measured only for the fixed test field.

2.2 Results

Figures 3(a), (b), and (c) show the measured ICC by Methods A, B and C, respectively. Open circles and filled circles show the measured values for fixed test fields and for variable comparison fields, respectively. If any method may be useful as a physical measure of ASW, ICC measured by it for the

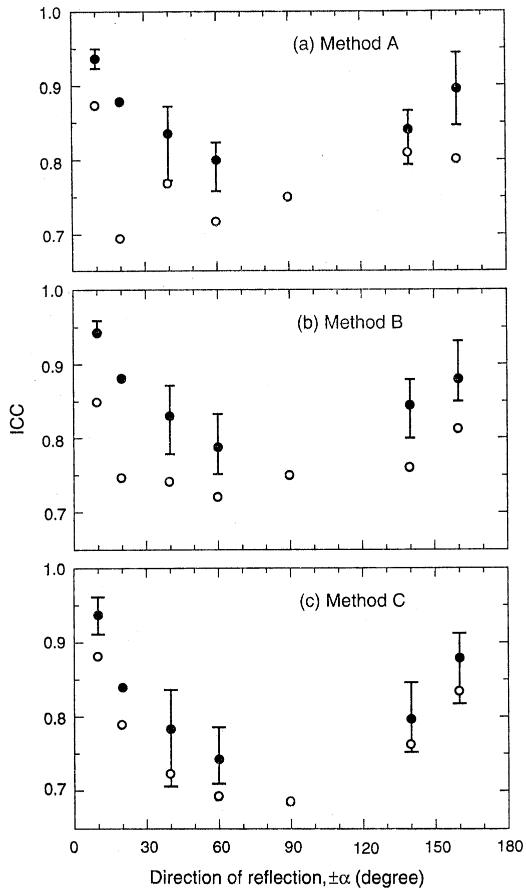

Fig. 3 Degree of interaural cross correlation measured by three kinds of measuring methods. Open circle, fixed test field; filled circle, variable comparison field; bar, 95% confidence limit.

comparison and the test fields must be identical.

The values for variable comparison fields (filled circles) by all methods show a similar tendency that ICC decreases as the azimuth angle of reflections gets close to $\pm\alpha=90°$. On the other hand, the values for fixed test fields (open circles) by the three methods show different tendencies. The values by Method A (Fig. 3(a)) do not coincide with the values for variable comparison fields except that they are within the 95% confidence limit of the variable comparison field at $\pm\alpha=40°$ and 140°. The minimum value of ICC for the fixed test field does not occur at $\pm\alpha=90°$, but at $\pm\alpha=20°$ and it does not show the monotonic tendency which the values for variable comparison fields do. The maximum difference between the comparison field and the test field is no less than 0.19 at $\pm\alpha=20°$. The values by Method B (Fig. 3(b)) decrease rapidly if the azimuth angle of reflection shifts slightly from the front to the lateral direction, and they change little between 20° and 140°. Furthermore, they were smaller than those for variable comparison fields at all azimuth angles. The difference between the values for the comparison field and the test field is as much as 0.13 at $\pm\alpha=20°$. The values by Method C (Fig. 3(c)) show the same tendency as the values for variable comparison fields. Namely, as the azimuth angle of reflections gets close to $\pm\alpha=90°$, the values by Method C decrease monotonously. Furthermore, though the values at $\pm\alpha=10°$, 20°, and 60° are outside of the 95% confidence limit of variable comparison fields, the maximum difference beyond the confidence limit is only 0.05 at $\pm\alpha=20°$.

Consequently, from these results, ICC measured by Method C can be regarded as the most useful physical measure for ASW of the music motif. Hereafter, ICC measured using a dummy head without artificial ear simulators and without A-weighting is termed DICC.

2.3 Discussion

The differences between the measured values by three kinds of measuring methods might be predicted by the following approximated analysis.

From Eq. (3), ICC is affected by a kind of source signal and the acoustical characteristics of a receiving system. Therefore, the differences between the results can be considered to be caused by those effects. But the source signal, the Mozart music motif, was common to the three measuring methods; its 1/3 oct. band spectrum is shown in Fig. 4. Figure 5 shows the amplitudes of the head-related transfer functions (HRTF) from a sound source placed in the front to the left ear of the KEMAR dummy head. The HRTF of the dummy head with artificial ear simulators has a significant resonance caused by the ear simulator around 2.5 kHz (Fig. 5(a)). On

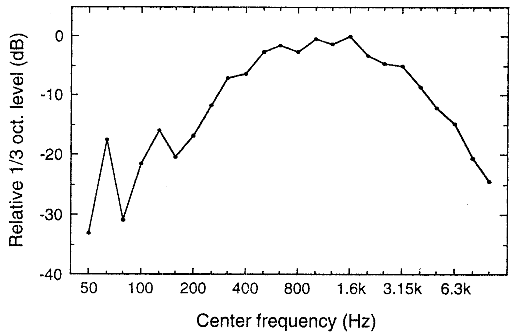

Fig. 4 1/3 oct. band spectrum of a music motif used as a source signal in measurements.

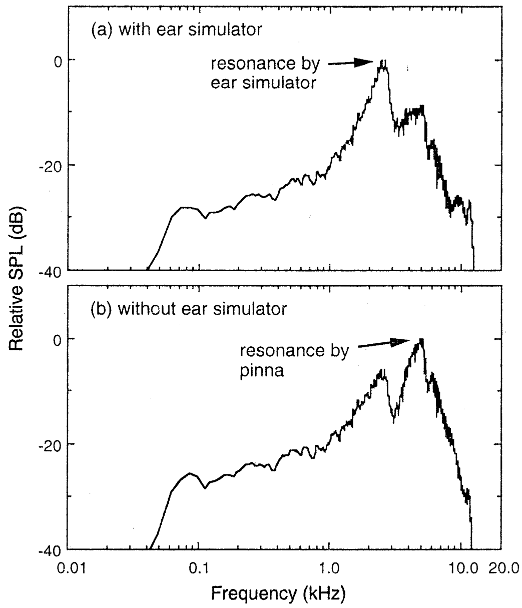

Fig. 5 Amplitudes of the head-related transfer functions from a sound source in front of KEMAR dummy head to his left ear. (a), with an ear simulator; (b), without an ear simulator.

the other hand, the HRTF of the dummy head without the ear simulator has a significant resonance caused by the pinna around 4 kHz (Fig. 5(b)), in place of the resonance caused by the ear simulator. Considering the spectrum of the music motif and the HRTF together, it can be inferred that A-weighting and the resonance of the ear simulator have a larger influence on frequency characteristics at the outputs from the dummy head than does the resonance of pinna. As a result there will be a correspondingly larger influence of the former on ICC.

If a direct sound and reflections are incoherent to each other, the interaural cross correlation function for the sound field consisted of them can be obtained by superposing the functions for a direct sound and reflections.[9] In concert halls where a direct sound comes from the front to a listener, the maximum of the function appears at time lag $\tau=0$. Namely, ICC for the sound field consisted of a direct sound and reflections is dominated by values at $\tau=0$ of the functions for reflections.

Figures 6(a), (b) and (c) show the interaural cross correlation functions for the music motif measured by three Methods A, B and C, respectively. The solid lines in Fig. 6 indicate the functions for a single source placed in the front as a direct sound ($\alpha=0°$). And then, too, they can be regarded as the auto correlation functions of the output signals from the dummy head, because the outputs from the left and the right ears of the dummy head are almost identical in this case. The absolute values at time lag $\tau=\pm 1$ ms for all the functions are less than 0.2. This suggests that the two reflections with a relative delay of 1 ms used in this measurement can be considered to be almost incoherent to each other.

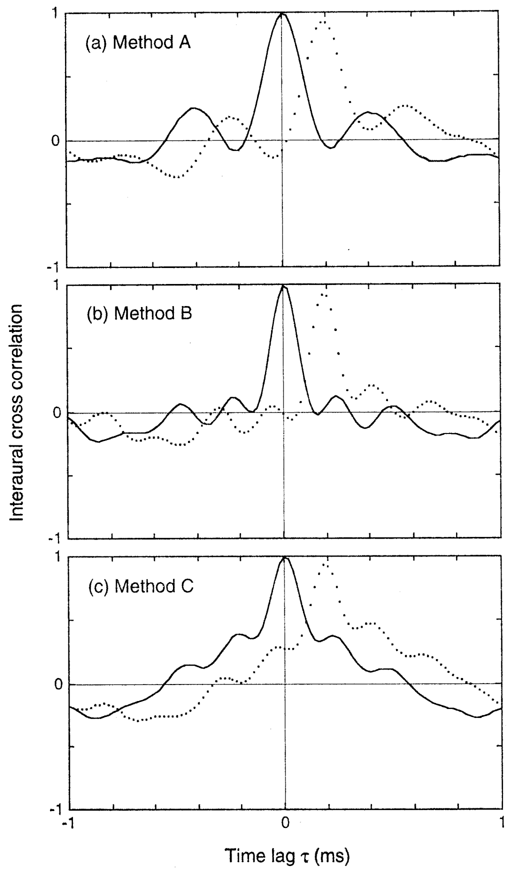

Fig. 6 Interaural cross correlation functions measured by three kinds of measuring methods. Solid line, a sound source at 0° (front); dotted line, a sound source at 20° (right).

The dotted lines in Fig. 6 indicate the functions for a single source placed at $\alpha=20°$ (right) as an example of a reflection. The behaviour of the function for a reflection coming from $\alpha=20°$ is very similar to that for a direct sound for any measuring method, except that the maximum appears at $\tau\approx$ 210 μs which equals the interaural time difference (ITD) caused by an incident sound from $\alpha=20°$. Namely, the value of the function for the reflection at $\tau=0$ is almost equal to the value of the function for a direct sound at τ which equals to ITD caused by only the reflection. Figures 7(a), (b) and (c) show the interaural cross correlation functions for the music motif radiated from a single source at various azimuth angle α on the right half of the horizontal plane, measured by three Methods A, B and C, respectively. For any method, the behaviour of the function does not differ from that for a direct sound ($\alpha=0°$) in case of $\alpha\leq 40°$. Even if α exceeds 60°, the behaviour is roughly similar to that for a direct sound.

Therefore, the behaviour of ICC for the sound field composed of a direct sound and reflections used in this measurement as a function of the azimuth angle $\pm\alpha$ of reflections can be approximately estimated from the behaviour of the interaural cross correlation function for a direct sound as a function of a time lag τ.

For a direct sound coming from the front as shown with solid lines in Fig. 6, the maxima of the

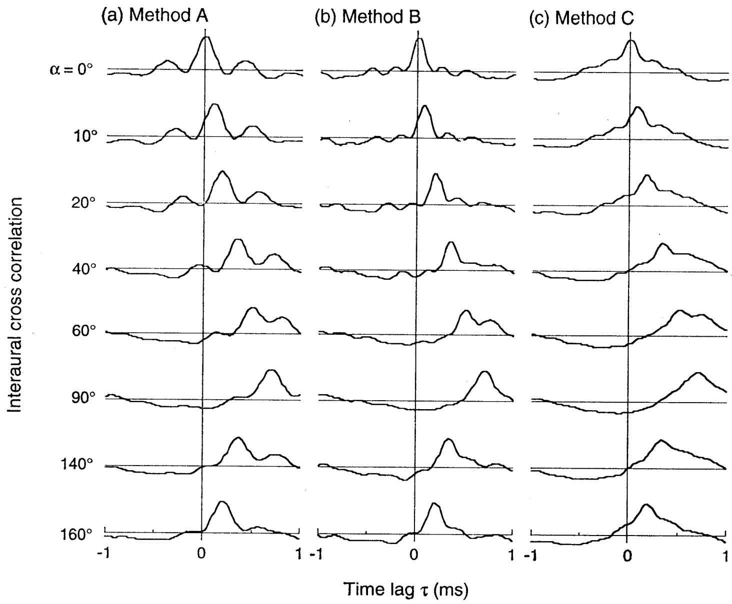

Fig. 7 Interaural cross correlation functions for a sound source at azimuth angle α on the right half of the horizontal plane measured by three kinds of measuring methods.

interaural cross correlation function measured by all methods appear at time lag $\tau=0$. But the behaviours of the three functions are different from each other. The function measured by Method A (Fig. 6(a)) changes considerably and periodically with the period corresponding to the ear simulator resonance frequency around 2.5 kHz shown in Fig. 5(a), and it decreases gradually as τ gets close to ± 1 ms on the whole. The first minimum appears at $\tau \approx 210\ \mu s$ which corresponds to ITD caused by a reflection comes alone from at $\alpha=20°$ (compare with the dotted line in Fig. 6(a)). The function by Method B (Fig. 6(b)) decreases rapidly, if τ shifts slightly from 0 ms and after then it little changes, though it shows a little periodical change with the period corresponding to the pinna resonance frequency around 4 kHz shown in Fig. 5(b). The function by Method C (Fig. 6(c)) decreases monotonously, as τ gets close to ± 1 ms, though it shows a little periodical change with the period corresponding to the pinna resonance frequency around 4 kHz shown in Fig. 5(b). For all kinds of measuring methods, the vehaviour of the interaural cross correlation function for a direct sound is in agreement with the behaviour of measured ICC for the fixed test field (see open circles in Fig. 3).

3. JUST NOTICEABLE DIFFERENCE OF DEGREE OF INTERAURAL CROSS CORRELATION AS A PHYSICAL MEASURE FOR ASW

An earlier study on just noticeable difference (jnd) of the degree of interaural cross correlation used various noises as source signals.[10] But now, ASW for music motif cannot be estimated from the data for noises. In this paper, jnd of DICC as a physical measure for ASW of a music motif is measured as a criterion for practical acoustical design.

3.1 Method

The psychological experiment was performed by the constant method, using the paired comparison method between the reference sound field with a fixed DICC and the comparison sound fields with different DICC.

3.1.1 Music motif

The motif used in this experiment was a 6 s section from bar 94 of the 4th movement of Mozart's Symphony No. 41 "Jupiter", which was the beginning part of the same motif as used by Barron and Marshall.[2]

3.1.2 Apparatus

Three loudspeakers were arranged at azimuth angles of 0° and ±45° from the median plane in an anechoic chamber. The distance between the center of the subject's head and loudspeakers was 1.5 m. The frequency characteristics of all loudspeakers were flat within ±5 dB in the frequency range from 100 Hz to 10 kHz.

3.1.3 Stimulus

Both the reference field and the comparison field consist of a direct sound and two reflections. The direct sound was radiated from in front of a subject and the reflections were radiated from the azimuth angles of ±45°. Reflection delays were 25 and 45 ms. The sound pressure levels of reflections were made equal to each other.

DICC was adjusted by controlling the energy ratio of reflections to a direct sound. DICC of the reference field was set at 0.5, 0.7, and 0.9. DICC of comparison field were set at 14 steps from 0.38 to 0.68, at 14 steps from 0.52 to 0.84 and at 12 steps from 0.84 to 0.94 for the reference fields with DICC=0.5, 0.7 and 0.9, respectively. The reason why the change of DICC of the comparison field was irregular was that DICC of the comparison field was controlled by changing the sound pressure levels of the reflections relative to the direct sound in step of 0.5 dB. From preliminary tests, these ranges were found to cover the region where the subject can easily discriminate ASW for the two sound fields. DICC was measured by using the KEMAR dummy head.

The sound pressure levels of all fields were constant at 70 dBA slow, peak measured at the left ear of the KEMAR dummy head without an artificial ear simulator.

3.1.4 Procedure

Paired comparison tests of ASW were carried out. A pair consisted of the reference field with a fixed DICC and one of the comparison fields with different DICC. In one series, the reference field preceded the comparison field, and *vice versa* in the other series. The time interval between presentation of the two fields was 1 s for both series. In each series, 40 pairs (14+14+12) were presented to the subject from the reference sound field with the highest DICC to the lowest. But pairs in the experiment for the identical reference field was arranged in random order and separated by an interval of 5 s. Each subject was tested eight times for each series alternatively and separately.

Each subject was tested individually, while seated, with his head fixed in a darkened anechoic chamber. The task of the subject was to judge which *ASW* was wider.

3.1.5 Subject

Eight male students with normal hearing sensitivity acted as subjects for the experiment.

3.2 Results and Discussion

In total, 128 responses to each pair were obtained (8 times ×2 series×8 subjects). For each reference field, the percentage of responses for which ASW for the comparison field was wider than that for the reference field was obtained. A z-transformation of the percentage was performed. The correlation coefficients between the z-value and DICC of the comparison field were 0.98, 0.99 and 0.99 for the reference fields with DICC=0.9, 0.7 and 0.5, respectively. This means that the distribution of responses to any reference field can be regarded as the normal one. Then, the regression equation was obtained by the least square method.

For each reference field, the value of DICC for the comparison field at $z=0$ was obtained from the regression equation. This value means that the percentage of responses was 50%. Namely, ASW for the comparison field with DICC of the value was judged to be equal to ASW for the reference field. The values were 0.90, 0.69 and 0.51 for the reference field with DICC=0.9, 0.7 and 0.5, respectively. The difference did not exceed 0.01. It can be considered that the subjects have the ability to judge ASW correctly.

In this paper, when the percentage of responses is above 75% or below 25%, ASW for two sound fields are considered to be distinguishable. Namely, jnds were defined as DICC at which the percentages were 75% ($z=+0.67$) and 25% ($z=-0.67$) and they were obtained from the regression line for each reference field. The results are shown in Table 1. jnds of ASW perceived to be wider (=75%) and narrower (=25%) than ASW for the reference field are almost identical for any reference field. But as DICC of the reference field becomes higher, jnd becomes smaller. This behaviour looks like Weber's law. Weber's ratios defined as Eq. (4) are also shown in Table 1.

$$K=\Delta DICC/(1-DICC)\,, \tag{4}$$

Table 1 jnd of DICC and Weber's ratio with regard to ASW.

DICC of reference sound field	Wider		Narrower	
	jnd of DICC	Weber's ratio	jnd of DICC	Weber's ratio
0.5	0.10	0.20	0.12	0.24
0.7	0.09	0.30	0.06	0.20
0.9	0.03	0.30	0.03	0.30

where K is Weber's ratio, $DICC$ is a reference field and $\Delta DICC$ is jnd. The ratios for all reference fields can be considered to be almost constant in the range from 0.2 to 0.3. Consequently, Weber's law is applicable to the perception of ASW at least in the region of DICC between 0.5 and 0.9.

4. ABSOLUTE VALUE OF ASW AS A FUNCTION OF DEGREE OF INTERAURAL CROSS CORRELATION AND BINAURAL SPL

In most past studies, ASW was only evaluated relatively, namely as "which was wider or narrower?" Absolute values of ASW (angle in degree) seem to be more useful for practical design. Only Keet[11] has measured ASW in absolute degrees of angle. But in his measurement, the degree of cross correlation between signals radiated from two loudspeakers was used as a physical measure, in place of the degree of interaural cross correlation between input signals to the left and right ears. The purpose of this measurement is to obtain an equation and a chart for estimation of the absolute values of ASW in degree as variables of DICC and the binaural summation of sound pressure level ($BSPL$).[12]

4.1 Method

Two kinds of psychological experiments (A and B) were performed in a darkened anechoic chamber. In Experiment A, the relative values of ASW were obtained and in Experiment B, the absolute values of ASW were measured in degree.

4.1.1 Music motif

The motif used in both experiments was a 6 s section from bar 94 of the 4th movement of Mozart's "Jupiter" Symphony (No. 41), which was the same motif as that used in the experiment on jnd.

4.1.2 Apparatus

For both experiments, three loudspeakers were arranged at azimuth angles of 0° and ±45° from the median plane in an anechoic chamber. The distance between the center of the subject's head and loudspeakers was 1.5 m. The frequency characteristics of all loudspeakers were flat within ±3 dB in the frequency range from 100 Hz to 10 kHz.

For quantitative judgments of absolute values of ASW in Experiment B, seventy-two light-emitting diodes (LED) were arranged at every 2.5° in the frontal semicircle of a subject on the horizontal plane including his aural axis. The LED radius was 1.5 m relative to the center of the subject's head. At any time only two LED symmetrical relative to the median plane shine simultaneously and their positions could be controlled by the subject himself, using a dial in his hand.

4.1.3 Stimulus

The sound field was the same as used in the experiment of jnd. It consists of a direct sound radiated from the front of a subject and two reflections radiated from the azimuth angle of ±45°. Reflection delays were 25 and 45 ms. The sound pressure levels of reflections were made equal to each other.

DICC was measured using the KEMAR dummy head and set from 0.4 to 0.9 in step of 0.1. DICC was adjusted by controlling the energy ratio of reflections to a direct sound. The BSPL defined by Eq. (5)[12] was measured using the KEMAR dummy head without artificial ear simulators and was set from 50 to 80 dBA in step of 10 dB. In total, 24 kinds of stimuli (6 DICC × 4 BSPL) were used in the experiments.

$$BSPL = 6\log_2(2^{L_l/6} + 2^{L_r/6}) \qquad (5)$$

where L_l and L_r are the sound pressure levels at the left and right ears, respectively.

4.1.4 Procedure

In Experiment A, a paired comparison test was carried out separately for each BSPL. For each BSPL, the test had 30 pairs of stimuli including reversals. As before, the interval between two stimuli was 1 s. All pairs of stimuli were arranged in random order and separated by an interval of 5 s. Each subject was tested individually and 20 times for each BSPL, while seated, with head fixed. The task of the subject was to judge which ASW is wider.

In Experiment B, eight of 24 stimuli were used to shorten the necessary time of experiment. Their DICC were 0.4 and 0.9 and their BSPL were 50, 60, 70 and 80 dBA. The subject's task was to adjust the position of the shining LED at the both horizontal ends of a sound image which he perceived. The angle in degree between two shining LED was regarded as the absolute value of ASW. The presentation of each stimulus was repeated every 1 s interval until the subject finished his task. The presentation order of different stimuli was random. The interval between different stimuli was 10 s. Each subject was tested individually and 20 times for each stimulus, while seated, with head fixed.

4.1.5 Subjects

Five and seven male students with normal hearing sensitivity acted as subjects for Experiments A and B, respectively. Five males acted as subjects for both experiments.

4.2 Results and Discussion

In Experiment A, 100 responses to each pair (5 subjects × 20 times) were obtained in total. The psychological scales of ASW were obtained using Thurstone Case V model.[13] Gulliksen's method[14] was also used for incomplete data. Figure 8 shows the psychological scale of ASW *vs.* DICC for each BSPL. For any BSPL, ASW were negatively correlated with DICC as reported by the past studies. The correlation coefficients between the psychological scale of ASW and DICC exceed −0.98 for all BSPL.

In Experiment B, 140 responses to each stimulus (7 subjects × 20 times) were obtained in total. The average value and the standard deviation (SD) of the absolute value of ASW were calculated for each stimulus. Figure 9 shows the absolute value of ASW *vs.* BSPL as a parameter of DICC. The minimum SD was 8.5° for the stimulus of DICC=0.9 and BSPL=50 dBA and the maximum SD was 32° for the stimulus of DICC=0.9 and BSPL=80 dBA. The average of SD was 18.3°. This value coincides with that obtained by Keet.[11] ASW for any DICC increases as BSPL grows and ASW for any BSPL decreases as DICC grows.

For each BSPL, absolute values of ASW for stimuli of DICC=0.5, 0.6, 0.7 and 0.8 were estimated by sharing the difference between the average value of the absolute value of ASW for DICC=0.4 and that for DICC=0.9 obtained in Experiment B, according to the differences between psychological

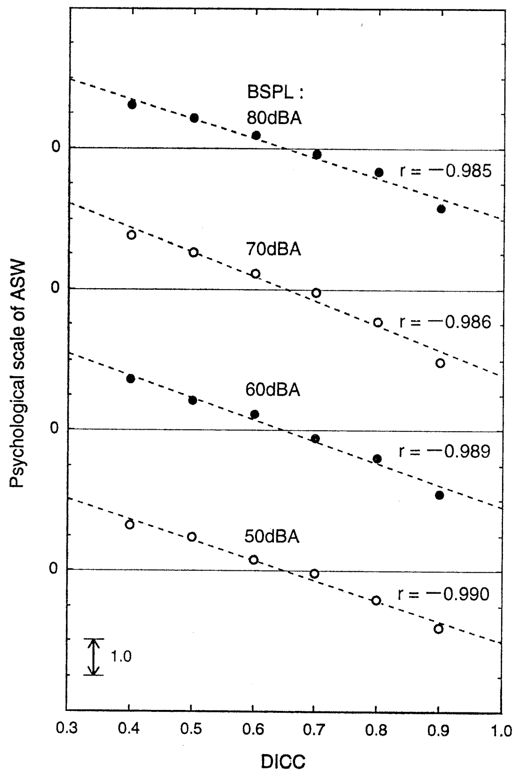

Fig. 8 Psychological scale of ASW as a function of DICC and as a parameter of BSPL.

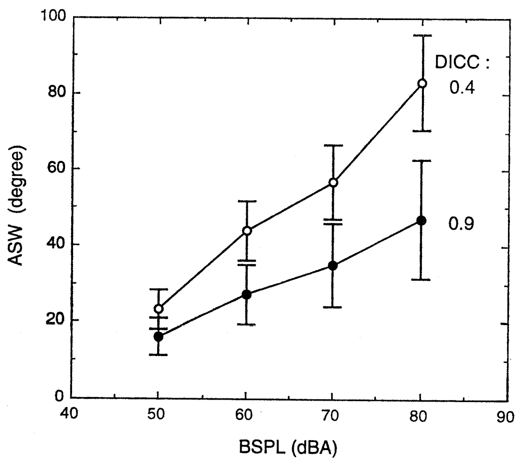

Fig. 9 Absolute value of ASW as a function of BSPL and as a parameter of DICC.

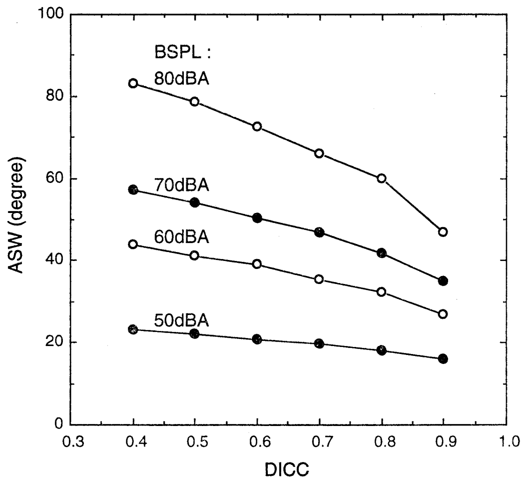

Fig. 10 Absolute value of ASW as a function of DICC and as a parameter of BSPL.

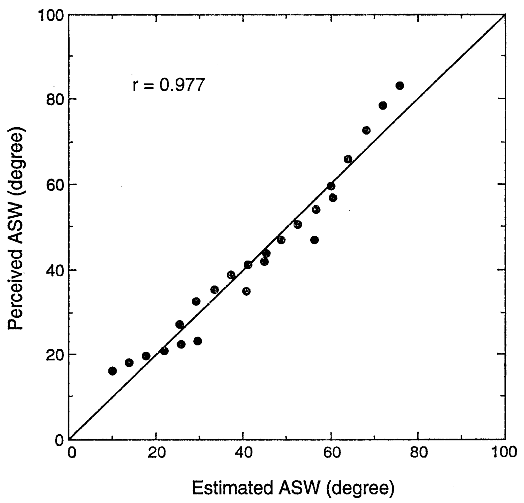

Fig. 11 Relation between perceived ASW and estimated ASW.

scales of ASW for stimuli of DICC=0.4, 0.5, 0.6, 0.7, 0.8 and 0.9 obtained in Experiment A. Figure 10 shows the absolute value of ASW *vs.* DICC as a parameter of BSPL for all stimuli.

To obtain an equation and a chart for evaluation of the absolute values of ASW in degree as variables of DICC and BSPL, multiple regression analysis was applied using data shown in Fig. 10. The criterion variable was ASW and the predictor variables were DICC and BSPL. Equation (6) shows the multiple regression equation.

$$ASW = -39.6X + 1.55Y - 31.9 \quad \text{(deggree)} \qquad (6)$$

where X is DICC and Y is BSPL (dBA).

Figure 11 shows the relation between the perceived ASW and the estimated ASW from Eq. (6). The correlation coefficient is 0.977. Consequently, it is clear that Eq. (6) is valid to estimate the absolute value of ASW in degree. From this equation, the increase of DICC by 0.1 decreases ASW by about 4° and the increase of BSPL by 1 dB increase about 1.6°. An increase of DICC by 0.1 is equivalent to a decrease of BSPL by 2.6 dB in ASW. The ratio +1.6°/+1 dB coincides with the result of Keet.[11] Figure 12 is the chart for evaluation of ASW obtained from Eq. (6), that is, the equal ASW contours for various DICC and BSPL.

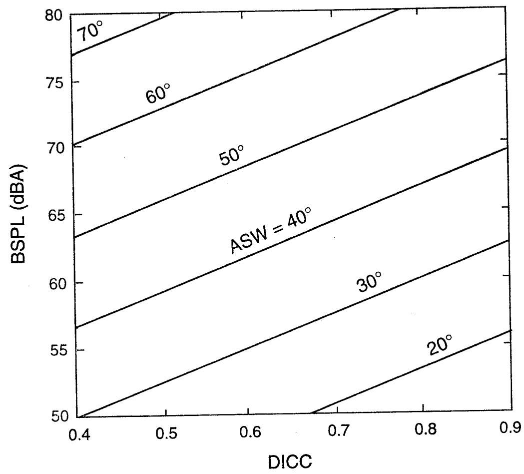

Fig. 12 Equal ASW contours for various DICC and BSPL.

5. CONCLUSIONS

For putting the degree of interaural cross correlation (ICC) to practical use as a single number physical measure for evaluation of auditory source width (ASW) in concert halls, the measuring method of ICC, the just noticeable difference (jnd) of ASW and absolute values of ASW (angle in degree) were investigated, using Mozart's Symphony No. 41 "Jupiter" as a standard source signal. The results of physical measurements and psychological experiments lead to the conclusions that:

(1) Using the music motif as the measurement signal, ICC when measured for dummy head signals without artificial ear simulators and without A-weighting, was found to describe with reasonable accuracy the results of psychological experiments on ASW by Barron and Marshall in which the same music motif was used as a source signal. Namely, it is useful as a single number physical measure for evaluation of ASW for a music motif. After this, it is termed DICC, to distinguish it from IACC measured with A-weighting.

(2) Weber's law is applicable to the perception of ASW. Weber's ratio as expressed by $\Delta DICC/(1-DICC)$, is found to be in the range from 0.2 to 0.3, where $DICC$ is for the reference field and $\Delta DICC$ is jnd.

(3) The absolute value of ASW in degree can be estimated by the following equation as functions of DICC and binaural sound pressure level (BSPL). $ASW = -39.6X + 1.55Y - 31.9$, where X is DICC and Y is BSPL (dBA).

These conclusions are, of course, valid for only a part of Mozart's Symphony No. 41 "Jupiter." It is necessary to investigate whether or not, they are valid for the other source signals with different frequency spectra. Originally, ICC and ASW depend on a kind of source signal as described in the beginning of this paper. Therefore, it may be a practical method to evaluate ASW using the same music motif as in Barron and Marshall's experiment which derived lateral energy fraction L_f.

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