THE RELATION BETWEEN SPATIAL IMPRESSION AND THE PRECEDENCE EFFECT

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ABSTRACT

This paper reviews results of listening tests on auditory spatial impression (ASI) that describe the relation between individual characteristics of spatial impression and the precedence effect. ASI is a general concept defined as the spatial extent of the sound image, and is comprised at least two components. One is auditory source width (ASW), defined as the width of a sound image fused temporally and spatially with the direct (preceding) sound image; the other is listener envelopment (LEV), defined as the degree of fullness of the sound image surrounding the listener, and which excludes the direct sound image for which ASW is judged. Listeners can perceive separately these two components of ASI, and their subjective reports demonstrate that they can distinguish between them. The perception of ASW and LEV has close connection with The precedence effect (the law of the first wave front). Acoustic signal components that arrive within the time and amplitude limits of the effect contribute to ASW, and those beyond the upper limits contribute to LEV. It is possible to control ASW and LEV independently by controlling physical factors that influence each of the components. It is well-known, for example, that the degree of interaural cross-correlation (ICC) is an important physical factor in the control of ASI. ASW can be predicted from ICC (and thereby controlled by the manipulation of ICC) regardless of the number and directions of arrival of sound sources. But measurements of ICC within 1/3-octave bands are preferred for estimating ASW, whereas the use of wide band and 1-octave band signals, as described in the ISO standard, are not. On the other hand, LEV cannot be controlled only through manipulation of ICC, as LEV is also affected by the spatial distribution of sounds (e.g., front/back energy ratio).

1. INTRODUCTION

Auditory spatial impression (ASI) is a multidimensional characteristic of human auditory sensation associated with the acoustics of a space. ASI comprises at least two perceptual components, auditory source width (ASW) and listener envelopment (LEV). Figure 1 illustrates a flowchart of human subjective evaluation of sound environment. An acoustic signal S(ω) radiated from a sound source is affected by a room transfer function R(ω) and arrives at the position of a listener. The composite acoustic signal is expressed as S(ω)xR(ω). This composite acoustic signal is then affected by head-related transfer functions Hl,r(ω) as it arrives at the entrances of the right and left ears as input signals to the auditory system. Subscripts l and r denotes the left and right ear, respectively. The input signals are expressed as S(ω)xR(ω)xHl,r(ω). Then the listener perceives auditory events, which include various groups of perceptual attributes, or "elemental senses." The elemental senses are divided into three groups. The first group concerns temporal attributes (rhythm, durability, reverberance, etc.). The second group involves spatial attributes (direction, distance, spatial impression, etc.), while the third relates to the quality attributes (loudness, pitch, timbre, etc.). Then the listener makes subjective judgment of each elemental sense, referring to his personal taste. Finally, he has his overall emotional response to the acoustics of the space with summing subjective judgment of each elemental sense, weighted again by referring to his personal taste.

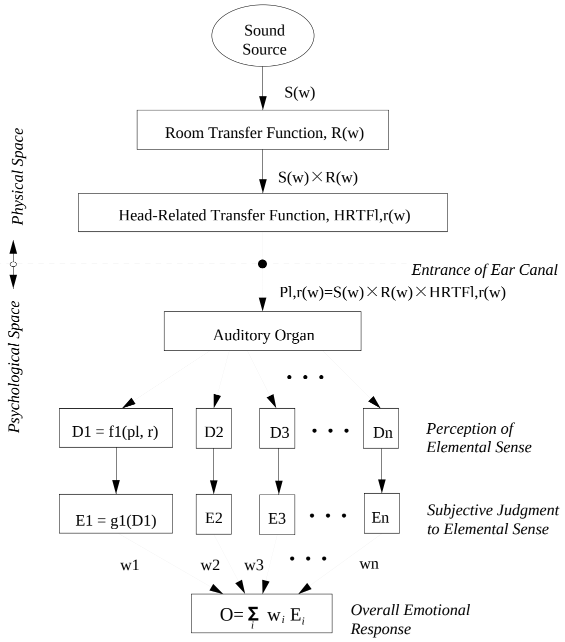


Figure 1. *Subjective evaluation system of sound environment*

Here, subjective judgments include differences between individuals, and consequently the influence of preferences on overall emotional response is unavoidable. On the other hand, the perception of elemental senses does not include differences between individuals. Therefore, needless to say, it is impossible to control and evaluate overall emotional responses of many and unspecified listeners to the acoustics of a space, since the responses will include differences between individuals. What can be generated, controlled, and evaluated is each elemental sense. For that purpose, it is important to make clear the acoustic cues (physical factors) predicting the perception of each elemental sense.

Among these elemental senses, it is well known that spatial impression is a most important characteristic of a listening space. The present author defines the term "spatial impression" as the spatial extent of the sound image. In the past, many different terms were used to describe spatial impression (See, for example, those listed by Blauert[1]). However, most of these terms were never distinctly defined. Therefore, it is not clear whether or not the "spatial impression" described by all of these terms are identical. In 1989, Morimoto and Maekawa demonstrated that spatial impression comprises at least two components and that a listener can discriminate between them[2]. One is auditory source width (ASW), defined as the width of a sound image fused temporally and spatially with the direct sound image, and the other is listener envelopment (LEV), the degree of fullness of sound images around the listener, excluding the precedent sound image composing ASW. In 1995, Bradley and Soulodre[3] also confirmed that spatial impression in concert halls is composed of at least the same two distinct senses. Figure 2 illustrates the concepts of the two types of spatial impression.

This paper reviews important outputs of many listening tests on auditory spatial impression by the author. First, the conditions to make a listener perceive spatial impression are discussed. Namely, the relation between spatial impression and the precedence effect is discussed. Secondary, the acoustic cues (physical factors) related to the prediction of spatial impression are investigated. Finally, answers to the question "How can auditory spatial impression be generated and controlled?" are given.

2. HYPOTHESIS ON RELATION BETWEEN SPATIAL IMPRESSION AND THE PRECEDENCE EFFECT

In the field of room acoustics, reflections are divided into an early and late part. The relevant time interval for early sound with music is 80ms while that for speech is 50ms. In the former way of thought[4][5], the early and late reflections contribute to ASW and LEV, respectively. However, Morimoto and Maekawa[2] demonstrated that the late reflections also contribute to ASW. Furthermore, the results of other experiments by Morimoto et al.,[6] indicated that the early reflections also contribute to LEV, vice versa. Thus, the division of reflections into the early and late parts does not always give a reasonable explanation of such an auditory perception, though the division is certainly convenient from a practical point of view.

Generally speaking, the reflections in a space distribute in not only time but also space and auditory events caused by those reflections are arranged in time and space, too. Therefore, the simple division of reflections into an early and late part in only time is not correct strictly. In such a sense, the division of reflections based on the precedence effect, e. g., the law of the first wave front and Haas effect, seems to be more essential, because the effect depends on time and space distribution of reflections. The author believes that, generally speaking, the listener perceives not only one sound image fused temporally and spatially with the direct sound image based on the precedence effect, but also the other ones caused by reflections not affected by the effect. Moreover, both sound images appear regardless of the delay times of reflections after the direct sound and each sound image has its own spatial extent. The purpose of this section is to evaluate the following hypothesis.

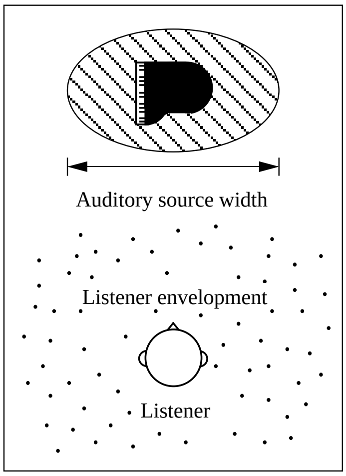


Figure 2. *Concepts of auditory source width (ASW) and listener envelopment (LEV).*

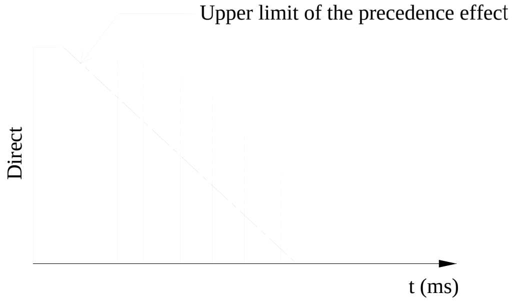


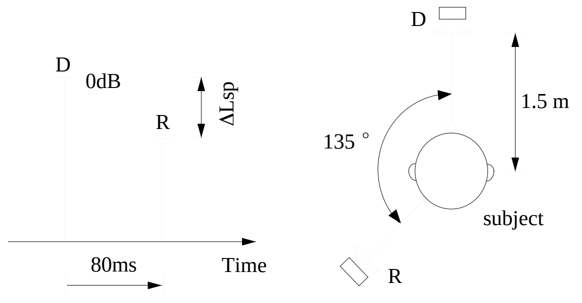
Figure 3. *Schematic explanation of the hypothesis on the relation between spatial impression and the precedence effect.*

Figure 3 is a schematic diagram to explain the hypothesis on the relation between spatial impression and the precedence effect. A sound field consists of a direct sound and several reflections. A dot-dash line indicates the upper limit of the precedence effect. Namely, reflections under the limit Therefore, solid and dotted lines of reflections indicate the components of reflections under and beyond the upper limit, respectively. The hypothesis is that the components of reflections under and beyond the upper limit of the precedence effect contribute to ASW and LEV, respectively.

3. EXPERIMENTS ON THE RELATION BETWEEN ASW AND THE PRECEDENCE EFFECT[7]

3.1. Method

Two experiments were performed to clarify the relation between ASW and the precedence effect. The music motif was used as a source signal in the experiment.



(a) (b)

Figure 4. *Impulse response of stimulus (a) and arrangement of loudspeakers (b) used in the first experiment.*

The purpose of the first experiment was to obtain the upper limit of the reflection level, which produced the precedence effect. The experiment was performed using the method of constant stimuli, keeping the time delay of a single reflection constant, and changing the sound pressure level of the reflection.

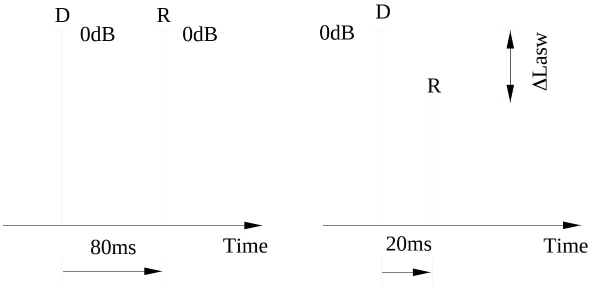
Figure 4 shows the impulse response of stimulus and the arrangement of loudspeakers. The time delay of the reflection was constant at 80ms. The sound pressure level of the direct sound was constant. The relative level of the reflection to the direct sound, ΔLsp was changed in eleven steps from -5dB to -15dB.

Each stimulus was presented to each subject 50 times in random order. The subject’s task was to mark down the direction and the range of the sound image on a circle on the recording sheet for each stimulus. When the subject perceived plural sound images, he was requested to mark down all those directions and ranges on the same circle.

In the second experiment, ASW created by a reflection, which did not produce the precedence effect, was measured. In the experiment, the sound pressure level of the reflection, which produced the effect, was obtained, when the reflection created the same ASW as a reflection, which did not produce the effect, created. The experiment was performed by again using the method of constant stimuli, comparing the ASW created by reflections that produced or did not produce the effect.

Figure 5 shows impulse responses of the stimuli used in the experiment. The arrangement of loudspeakers was the same as in the first experiment (Fig. 4). According to the results of the preparatory experiment, Fig. 5(a) was the impulse response of the stimulus, which did not produce the effect. The time delay and the relative level of the reflection to the direct sound were fixed at 80ms and 0dB, respectively. Figure 5(b) was the impulse response of the stimulus, which produced the effect, even if the relative sound pressure level of the reflection to the direct sound was 0dB. The time delay of the reflection was fixed at 20ms. The relative sound pressure level of the reflection to the direct sound, ΔLasw was changed in eleven steps of 1dB from -5dB to -15dB. The binaural summation of loudness[8] of the total sound pressure levels of the direct sound and the reflection of all stimuli were constant.

A pair of the stimulus not producing the effect (Fig. 5(a)) and one of the eleven stimuli producing the effect (Fig. 5(b)) was delivered. The subject was requested to answer which ASW was wider. Each pair was presented to each subject fifty times in random order.



(a) (b)

Figure 5. *Impulse responses of used in the second experiment.*

3.2. Results and Discussion

The data analysis of both experiments was done separately for each subject by using the normal-interpolation process. The percentage of split of sound image was obtained from the results of the first experiment. And also, the percentage that ASW of a stimulus, which produced the effect, was wider than ASW of a stimulus, which did not produce the effect, was obtained from the second experiment. Furthermore, Z-transformations of those percentages were performed and the regression lines and the correlation coefficients were obtained neglecting data of 0 and 100%.

Both of two correlation coefficients were almost 1.0. This means that both experimental data show the normal distribution. The average value was obtained at $z = 0$. The coefficients for all results for all subjects exceeded 0.93. The average value of the first experiment, [ΔLsp], means the relative sound pressure level of the reflection to the direct sound, which splits a sound image with the probability of 50%. Namely, it is the upper limit of level of a reflection, which produces the effect. Meanwhile, the average value of the second experiment, [ΔLasw], means that ASW by the reflection of [ΔLasw] which produces the effect (Fig. 5(b)) is equal to ASW by the reflection which does not produce the effect (Fig. 5(a)). In other words, it can be considered that the part of the reflection under [ΔLasw] contributes to create ASW in case (a), because ASW is independent of the time delay of a reflection[9][10][11].

Table 1 shows [ΔLsp] and [ΔLasw] for each subject. Surprisingly, the two values for subject A are identical. The maximum difference between [ΔLsp] and [ΔLasw] is 0.7dB for subject B. From these results, it can be considered that [ΔLsp] is equal to [ΔLasw].

Table 1. *Comparison of [ΔLsp] with [ΔLasw] in dB.*

Subject	[ΔLsp]	[ΔLasw]
A	-7.0	-7.0
B	-9.3	-10.0
C	-10.3	-9.7

3.3. Conclusion

The results of the experiments substantiate the hypothesis that components of the reflection under the upper limit of the precedence effect contribute to ASW.

4. EXPERIMENTS ON THE RELATION BETWEEN LEV AND THE PRECEDENCE EFFECT[12]

In this section, to examine the hypothesis, four thresholds were measured by the listening tests: image-split which corresponds to the upper limit of the precedence effect, LEV, echo perception and echo disturbance.

4.1. Method

The music motif was used as a source signal in the experiment. Figure 6 shows the impulse response and the arrangement of loudspeakers of a test sound field used as a stimulus. The sound field consisted of a direct sound placed in front and two reverberation signals placed at ±135 °. Their reverberation times were constant at 2.0 s and their frequency characteristics were flat. Reverberation delays were 80 and 81ms. The sound pressure level of the direct sound was kept constant and the relative sound pressure level of the first component of reverberation signals (ΔL) to the direct sound were changed in random order. ΔL were set at 11 steps from -39.6 to -19.6dB, at 9 steps from -11.6 to -3.6dB and at 11 steps from -52.6 to -42.6dB for perceptible thresholds of image-split and LEV, echo disturbance and echo perception, respectively.

The task of the subject was to map all sound images which he perceived in case of the threshold of image-split and to answer whether he could perceive each auditory phenomenon or not, in other cases, after each presentation of stimulus. Each subject was tested 51 times for each stimulus. Experiments of four kinds of threshold were performed separately in the order image-split, LEV, echo perception and echo disturbance.

4.2. Results and Discussion

The data reduction was done separately for each subject. All thresholds were obtained by using the normal-interpolation process. Figure 7 shows measured values of four kinds of threshold with their standard deviations together for each subject. There is little difference between individuals for all four thresholds. The difference between thresholds of image-split and echo perception is about 20dB. This means that the subjects could discriminate between them.

The difference between image-split and LEV is small for any subject. The threshold of LEV is within the standard deviation of image-split except for subject B. From these results, the threshold of image-split and LEV can be considered to be identical. This supports the hypothesis that the components of reflections beyond the upper limit of the precedence effect contribute to LEV, since the threshold of image-split corresponds to the upper limit. In other words, it is necessary to provide reflections beyond the upper limit in order to generate LEV. Meanwhile, the threshold of echo disturbance is higher than that of LEV by about 20dB. This means that reflections beyond the threshold of image-split do not always occur echo disturbance, but contribute to LEV.

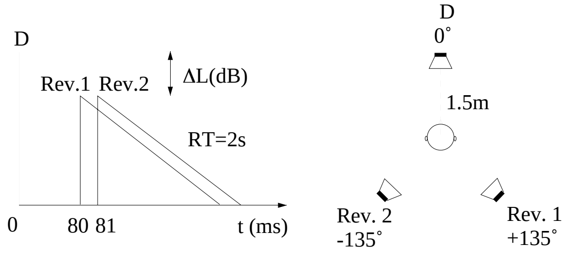


Figure 6. *Impulse response of stimulus and arrangement of loudspeakers used in the experiment.*

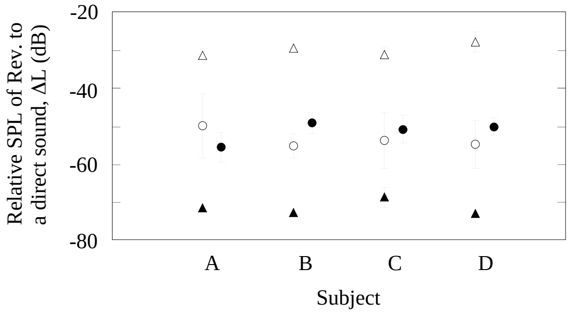


Figure 7. *Four kinds of threshold and their standard deviations. Open circle, image-split; closed circle, listener envelopment; open triangle, echo-disturbance; and closed triangle, echo perception.*

4.3. Conclusion

The results of experiments support the hypothesis that the components of reflections beyond the upper limit of the precedence effect contribute to LEV.

5. CONCLUSIONS ON RELATION BETWEEN SPATIAL IMPRESSION AND THE PRECEDENCE EFFECT

It seems that the results of experiments shown in this section constitute strong evidence in favor of the hypothesis that the components of reflections under and beyond the upper limit of the precedence effect contribute to ASW and LEV, respectively. Accordingly, it is possible to control ASW and LEV independently by controlling physical factors for each component. The important is that it is necessary to provide reflections beyond the upper limit in order to generate LEV.

6. MEASURING METHOD OF INTERAURAL CROSS - CORRELATION AS A PHYSICAL FACTOR FOR AUDITORY SOURCE WIDTH

It is general knowledge that reflections from the lateral directions are necessary to generate ASW[10][13]. The degree of interaural cross-correlation (ICC) is well known as a physical factor for ASW. Morimoto et al.,[14] indicated that ASW perceived in different sound fields with the same ICC are equal to each other, regardless of number and arriving direction of reflections. Namely, ICC is effective for evaluating ASW when reflections arrive from arbitrary directions in an enclosure like a concert hall. There has been a demand for measurements of ICC as a physical measure (factor) for ASW. It is general knowledge that ICC has a negative correlation with ASW. Standardization of the measurement has been also discussed by ISO[15]. This section classifies ICC into three kinds of measures based on measuring methods and discusses an effective measuring method of ICC, comparing ICC and ASW for different source signals: music motif, wide-band noise, 1/1 oct. band noise and 1/3 oct. band noise.

Note what is important for a physical measure to evaluate and control a subjective effect is that it is well correlated with the subjective effect.

6.1. Definition of Interaural Cross-correlation

ICC is generally defined as follows;

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

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

$$\Phi_{lr} = \lim_{T\to\infty} \frac{\dfrac{1}{2T}\displaystyle\int_{-T}^{+T} p_l(t)\,p_r(t-\tau)\,dt}{\dfrac{1}{2T}\sqrt{\displaystyle\int_{-T}^{+T} p_l^2(t)\,dt}\sqrt{\displaystyle\int_{-T}^{+T} p_l^2(t)\,dt}} \qquad (2)$$

where $p_l(t)$ and $p_r(t)$ are the input signals to the left and right ears, respectively and described as follows.

$$\begin{aligned} p_l(t) &= s(t) * r(t) * h_l(t) \\ p_r(t) &= s(t) * r(t) * h_r(t) \end{aligned} \qquad (3)$$

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.

6.2. Physical Measures for ASW based on Interaural Cross- correlation

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.

Several physical measures based on ICC have been already proposed. The measured value of ICC depends on how $h(t)$ in Eq. (3) is treated, even for the same source signal. $h(t)$ can be considered as the acoustical characteristics of a receiving system in ordinary acoustical measurements. The way $h(t)$ is treated is the key to the usefulness of the measure. Three measures of ICC are listed in Table 2, considering physical factors relating to $h(t)$. IACC(I) was proposed in the ISO[15] and IACC(A) is Ando's[16]. DICC was proposed by Morimoto and Iida[13]. IACC(I) is measured by using a dummy head with artificial ear simulators (B & K Type DB-100) and without A-weighting. IACC(A) is measured by using a dummy head without the artificial ear simulators and with A-weighting. DICC is measured by using a dummy head without the artificial ear simulators and without A-weighting.

Table 2. *Three physical measures for ASW based on ICC*

Physical measure	Ear canal simulator	A-weighting
IACC(I)	YES	NO
IACC(A)	NO	YES
DICC	NO	NO

To investigate availability of each ICC listed in Table 2, ASW and ICC for music motif, wide-band noise, 1/1 oct. band noise and 1/3 oct. band noises are compared.

6.3. Comparison between ASW and ICC Measures for Music Motif[13]

6.3.1. Experimental Method

The results of the experiment by Barron and Marshall[11] were utilized in this investigation. In their experiment, Mozart's "Jupiter" Symphony No.41 was used as a source signal. The measurements of ICC were conducted using the same sound field as Barron and Marshall's and the KEMAR dummy head.

At first, the ICC for each of the variable comparison fields was measured. 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 which were measured by Barron and Marshall (see Fig. 7 in [11]). Next, the ICC of the fixed test fields was measured. 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 - 9dB. ICC for $\pm\alpha = 90°$ was measured only for the fixed test field.

6.3.2. Experimental Results and Discussion

Figures 8(a), (b), and (c) show the measured IACC(I), IACC(A), and DICC, 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 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

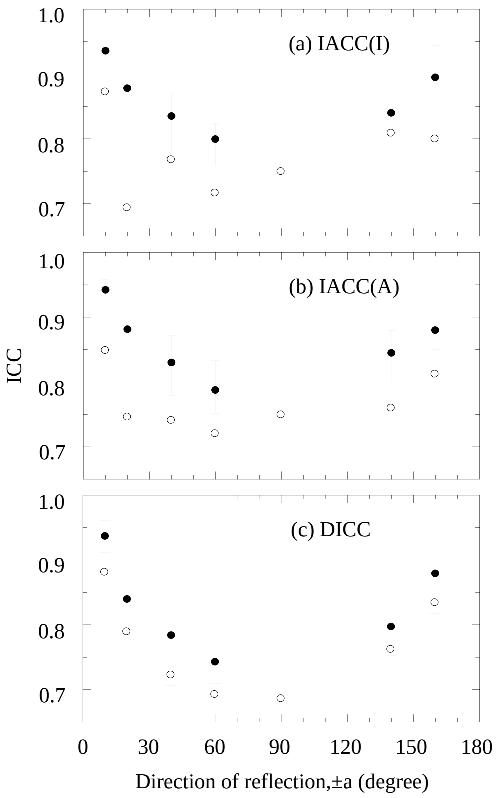


Figure 8. *Degree of interaural cross-correlation for music motif measured by three kinds of measuring method. Open circle, fixed test field; filled circle, variable comparison field; bar, 95% confidence limit.*

show different tendencies. The values for fixed test fields by IACC(I) and IACC(A) do not coincide with the values for variable comparison fields. However, the values for fixed test fields by DICC coincide with the values for variable comparison fields.

Consequently, DICC is effective to evaluate and control ASW of the music motif including such frequency components as Mozart's "Jupiter" Symphony No. 41, but IACC(I) and IACC(A) are not. Note that this conclusion was derived from the experiment where the frequency components of a direct sound and reflections were identical. When they are different, ICCavg by Morimoto et al.,[17], the averaged ICC value of seven 1/1 oct. band for Fc = 125Hz - 8kHz, is effective to evaluate and control ASW of the music motif more than DICC.

6.4. Comparison between ASW and ICC Measures for Wide-band Noise[18]

6.4.1. Experimental Method

The comparisons were performed using a simple sound field composed of a direct sound source and two discrete lateral reflections. The sound pressure level of the reflections relative to the direct sound was fixed at - 6dB. The directions of lateral reflections were changed from ±18 ° to ±90 ° in steps of 9 °.

Pink noises which were incoherent each other were radiated from a frontal and two lateral loudspeakers. The lower cut-off frequency was fixed at 200Hz.The higher cut-off frequency (Fhc) was changed at 8kHz, 4kHz, 2kHz and 1kHz. The total sound pressure level of all stimuli was constant.

ASW generated by pairs of reflections from different directions were compared for each Fhc, separately. IACC(I), IACC(A) and DICC of each stimulus were measured by using the KEMAR.

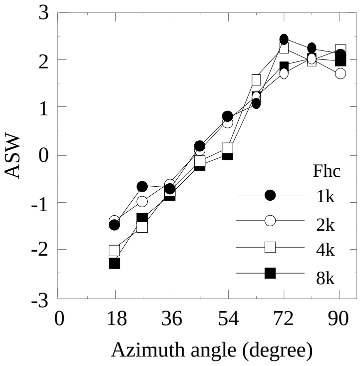


Figure 9. *ASW for wide-band noise as a function of azimuth angle of lateral reflections. The parameter, Fhc is the higher cut-off frequency.*

6.4.2. Experimental results and discussion

Figure 9 shows the psychological scales of ASW obtained from the experiments by using Thurstone case V. The closer the azimuth angle of lateral reflections gets to 90 °, the wider ASW grows for any Fhc. Furthermore, ASW for any Fhc are almost identical. This means that higher frequency components than 1kHz do not contribute to ASW at all, for the wide band source signals including low frequency components below 1kHz.

Figures 10(a), (b) and (c) show measured values of IACC(I) and IACC(A) and DICC, respectively. All of IACC(I) and IACC(A) and DICC for Fhc=2k, 4k and 8kHz do not depend on the direction of reflections and have no correlation with ASW shown in Fig. 10. For only Fhc=1kHz, they have a negative correlation with ASW.

In conclusion, all of IACC(I), IACC(A) and DICC are not effective to evaluate and control ASW for wide-band noise including frequency components above 1kHz.

6.5. Comparison between ASW and ICC Measures for 1/1 and 1/3 oct. Band Noises[18][19]

ISO3382[15] recommends the use of wide band and 1/1 oct. band noise signals to evaluate ASW. The author demonstrated that ICC with 1/3 oct. band is well correlated with ASW but ICC with a wide band is not[18]. There is no evidence that ICC with 1/1 oct. band is well correlated with ASW.

6.5.1. Experimental Method

The method used in this experiment was the same as that used in Section 6.4. The test signals were 1/1 oct. band and 1/3 oct. band

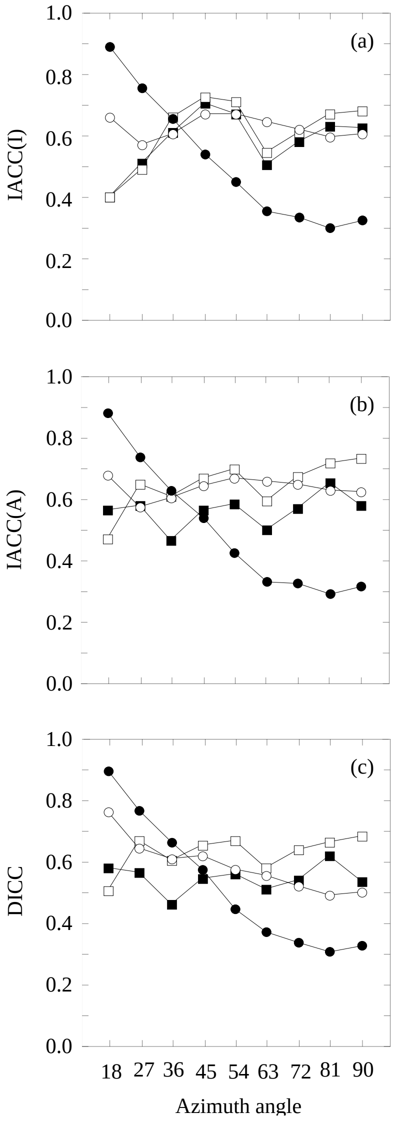


Figure 10. *Measured values of IACC(I) (a), IACC(A) (b) and DICC (c) for wide-band noise as a function of azimuth angle of lateral reflections. The parameter, Fhc is the higher cut-off frequency.*

noises. Their center frequencies (Fc) were 500Hz, 1kHz, 2kHz and 4kHz. The total binaural sound pressure level of stimulus was constant. ASW generated by pairs of reflections from different directions were compared, separately for each Fc and for each band noise. ICC was measure by DICC method, since the difference the difference between measured values by three different methods can be neglected because of a narrow band of 1/1 and 1/3 oct. bands.

6.5.2. Experimental Results and Discussion

Figure 11 shows ASW and measured ICC for each 1/1 oct. band noise. ASW has a highly negative correlation with ICC for Fc=500Hz and 1kHz. However, ASW has a positive correlation with ICC for Fc=2kHz and ASW has no correlation with ICC for Fc=4kHz. Figure 12 shows ASW and measured ICC for each 1/3 oct. band noise. ASW has a highly negative correlation with ICC except for Fc=4kHz. However, if examined individually in the case of Fc=4kHz, ASW perceived by six of twelve subjects has negative correlated with ICC. These results suggest that the critical band works also in the perception of ASW and that there are differences between individuals in the width of the band.

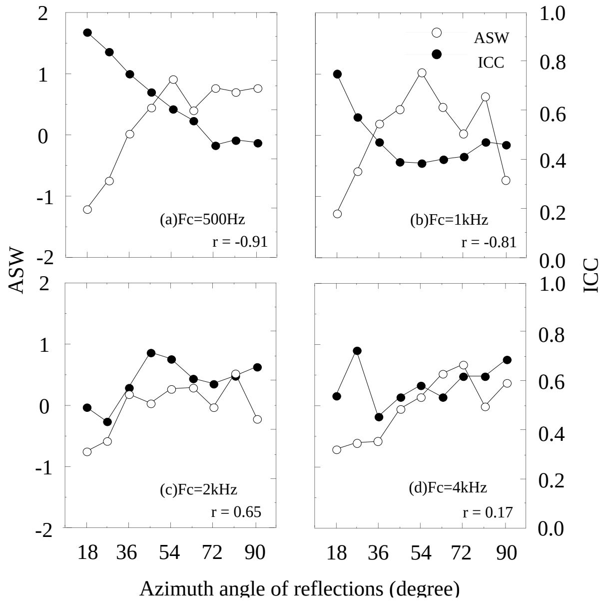


Figure 11. *ASW and measured ICC for 1/1 oct. band noise as a function of azimuth angle of lateral reflections. The parameter is the center frequency.*

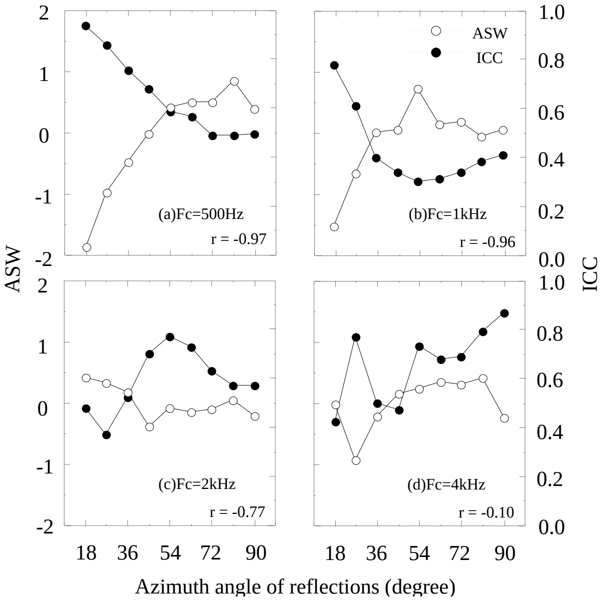


Figure 12. *ASW and measured ICC for 1/3 oct. band noise as a function of azimuth angle of lateral reflections. The parameter is the center frequency.*

Accordingly, measurements of ICC with 1/3 oct. bands are preferred for evaluating ASW, whereas the use of wide band and 1/1 oct. band signals as described in the ISO standard are not.

6.6. Conclusions

The comparison of measured values of ICC with ASW indicates that; (1) IACC(I) proposed by ISO and IACC(A) by Ando are not effective to evaluate ASW generated by the music motif and the wide-band noise. (2) On the other hand, DICC proposed by the author is effective to evaluate ASW generated by music motif, but not by wide-band noise. (3) The appropriate band width is not 1/1 oct. band recommended by ISO 3383.

7. PHYSICAL FACTOR FOR LEV: THE ROLE OF REFLECTIONS FROM BEHIND THE LISTENER IN SPATIAL IMPRESSION[20]

Yamamoto and Suzuki[21] reported that one of the subjective factors for sound in rooms correlates with Front / Back energy ratio. However its subjective meaning was not made clear. The author assumed that it must be LEV. The purpose of this section is to make clear the role of reflections from behind the listener in the perception of spatial impression. Although it is already clear that ASW is perceived regardless of whether or not the reflections arrive from either the frontal or rear directions, in the experiments the effects of reflections from behind the listener on not only LEV but also ASW were investigated as a parameter of Front / Back energy ratio and C-value. Figure 13 shows the definition of Front / Back energy ratio. In this case, however, the direct sound and reflections coming from lateral directions at exactly ±90° are excluded.

7.1 Experimental Method

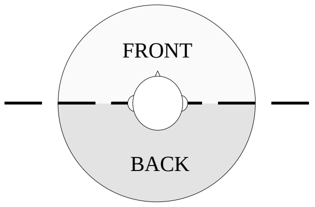
The music motif was used as a source signal in this experiment. The parameters were Front / Back energy ratio and C-value.

Six loudspeakers were arranged at azimuth angles of 0° and ±45° from the median plane, that is, they are arranged symmetrically to the aural axis. The impulse response of the sound field as a stimulus consists of a direct sound and four early discrete reflections and four reverberation signals. The reverberation time was constant at 1.5s.

The directions and the relative sound pressure levels of early reflections and reverberations depend on Front / Back energy ratio and C-value of stimulus. However the sound pressure levels of reflections and reverberations from the left and the right were the same and they were radiated from loudspeakers arranged symmetrically to the aural axis so that DICC of each part of the early reflections and the reverberations as well as the whole part (early + reverberation) of a sound field as a stimulus might be constant.

Front / Back energy ratio was set at -15, -7.5, 0, +7.5, +15.0dB. Moreover, Front / Back energy ratio in the early part and that in the reverberant part were the same. C-value was set at -11, -1, +9dB. DICC of the whole part of a sound field of all stimuli were constant at 0.65 ± 0.05 measured by the KEMAR dummy head. The sound pressure levels of all stimuli were constant.

Paired comparison tests of not only LEV but also ASW were performed. But, the experiment for ASW were performed under the conditions where Front / Back energy ratio was changed at a C-value of only -1.0dB. The tasks of the subject were to judge which LEV is greater and which ASW is wider.



$$\text{F/B energy ratio} = 10 \log_{10} \frac{\text{FRONT}}{\text{BACK}} \text{ (dB)}$$

Figure 13. *Definition of Front / Back energy ratio.*

7.2 Experimental Results and Discussion

The psychological scales of LEV and ASW were obtained using Thurstone Case V model. Notice that a difference of 0.68 on the psychological scale corresponds to jnd.

Figure 14 shows the psychological scale of LEV as a function of Front / Back energy ratio and as a parameter of C-value. For any C-value, LEV increases as Front / Back energy ratio decreases. Furthermore, the difference between the maximum and the minimum LEV exceeds 0.68 for any C-value. This means that Front / Back energy ratio significantly affects LEV a listener perceives. Namely, the LEV increases as the sound energy from behind the listener increases.

Figure 15 shows the psychological scale of ASW as a function of Front/Back energy ratio at a C-value of only -1.0dB. Noticeably, the difference between ASW for any Front / Back energy ratio is within 0.68. This result coincides with the results that ASW perceived by any sound field with the same DICC are identical From the results about LEV and ASW obtained in these experiments, it can be clearly confirmed again that a listener can perceive LEV and ASW separately.

7.3 Conclusions

LEV is changed significantly by Front / Back energy ratio even if DICC is kept constant. Also, LEV increases as the Front/Back ratio decreases. That is, LEV increases as the energy of the reflections from behind a listener increases. LEV does not seem to be affected significantly by C-value and ASW is not changed by Front / Back energy ratio if DICC is kept constant.

8. HOW CAN AUDITORY SPATIAL IMPRESSION BE GENERATED AND CONTROLLED?

First of all, note that auditory spatial impression comprises at least two components. One is auditory source width (ASW) and the other is listener envelopment (LEV). Creation of them is strongly related to the precedence effect.

With ASW, it is general knowledge that lateral reflections are necessary to generate ASW. ASW generated by lateral reflections can be evaluated and controlled by the degree of interaural cross-correlation (ICC). Equal ASW is perceived in different sound fields

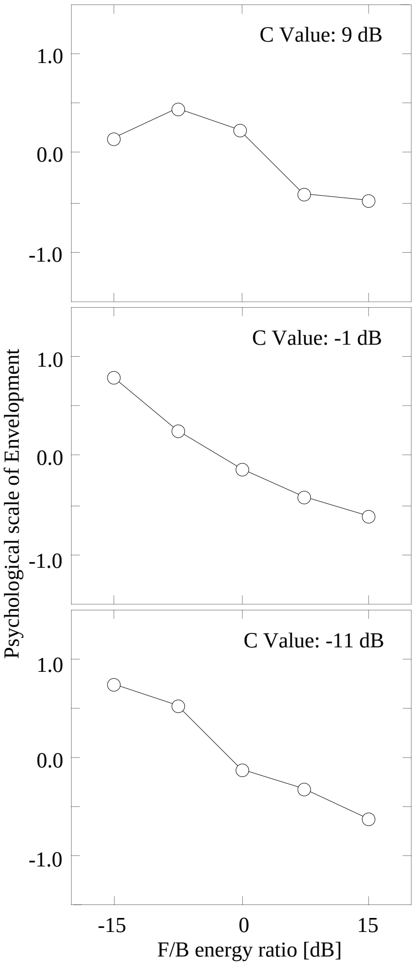


Figure 14. *LEV as a function of a Front/Back energy ratio and as a parameter of C value.*

with the same ICC, regardless of number and arriving direction of reflections. The degrees of interaural cross-correlation measured by the KEMAR dummy head without artificial ear simulators and A-weighting, so-called DICC proposed by the present author is effective to evaluate and control ASW for music motifs consisting of such frequency components as Mozart's Jupiter Symphony (No.41), but not effective for wide-band noises including frequency components above 1.5kHz. Furthermore, when the frequency components of a direct sound and reflections are different, ICCavg by Morimoto et al.,, the averaged ICC value of seven 1/1 oct. band for Fc = 125Hz - 8kHz, is more effective than DICC even for the music motif. On the other hand, both of the degrees of interaural cross-correlation proposed by Ando and ISO3382 are effective for neither the music motif nor the wide-band noise. In frequency band analyzing of ICC, an appropriate band width is 1/3 oct. band, but not 1/1 oct. band recommended by ISO3382.

With LEV, LEV depends on DICC as well as ASW. However, the acoustic components beyond the upper limit of the precedence effect are necessary to generate LEV. Furthermore, the components from behind the listener generate greater LEV.

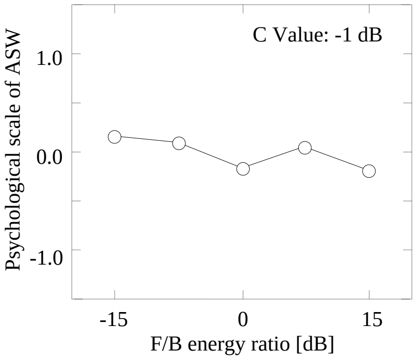


Figure 15. *ASW as a function of a Front/Back energy ratio.*

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