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Estimation of auditory source width (ASW): I. ASW for two adjacent 1/3 octave band noises with equal band level

Kazumi Ueda* and Masayuki Morimoto**

**The Graduate School of Science and Technology, Kobe University, Rokkodai, Nada, Kobe, 657 Japan*
and Comprehensive Housing R & D Institute, Sekisui House, Ltd., 6–6–1, Kabutodai, Kizu-cho, Kyoto, 619–02 Japan
***Faculty of Engineering, Kobe University, Rokkodai, Nada, Kobe, 657 Japan*

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The authors formulated a technical prediction model of auditory source width (ASW). By the model, ASW for any stimulus can be estimated by summing up 1/3 octave band ASW. It is necessary, however, to multiply weighting factor W by each 1/3 octave band ASW before summation. In this paper, the psychological experiment was performed to examine the validity of the model under the very fundamental condition that the number of adjacent 1/3 octave bands was two and each band had equal sound pressure levels. The results of the quantitative judgments of ASW confirmed the validity of the model and showed that the weighting factor depended on the frequency band and the subject. Roughly speaking, the weighting factor for 500 Hz band was larger than those for the other frequency bands under the given condition.

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

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1. INTRODUCTION

The broadening of a sound image is an important psychological factor of the sound field. One of authors has shown that the broadening of a sound image consists of two elemental senses at least.[1] One is auditory source width (ASW) and the other is feeling of envelopment. The former is the width of a sound image perceived to be fused temporally and spatially with a direct sound, and the latter is the fullness of a sound image around a listener, excluding a sound image relating to ASW.

In the past, ASW has been studied in various terms such as spatial impression, apparent source width, auditory spaciousness and so on.[2-4] Well-known physical factors to estimate ASW are lateral energy fraction,[2] the degree of interaural cross correlation,[5-9] and the sound pressure level.[8,10] Generally speaking, ASW increases as the lateral energy fraction increases, the degree of interaural cross correlation decreases, and the sound pressure level increases. It is, however, reported that the presence of low frequency components increases ASW.[7] This fact infers that the exact ASW estimation demands not only the single values of these physical factors which are measured over all frequencies, but also their frequency characteristics.

One of authors has proposed DICC (the degree of interaural cross correlation measured without A-weighting using a dummy head without ear simulators) and DICC (1600) (DICC measured through a low-pass filter with cut-off frequency of 1,600 Hz) as

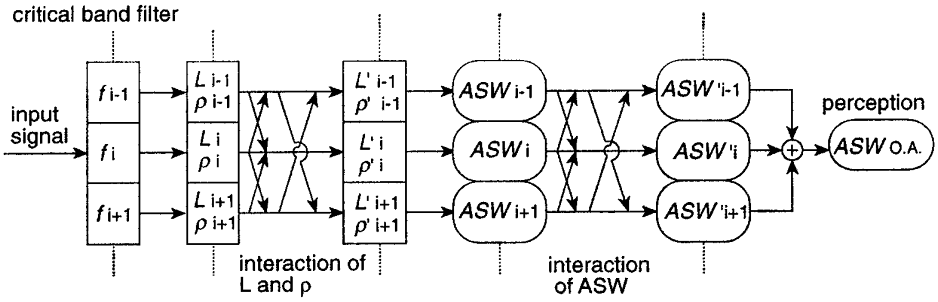

Fig. 1 Functional model of ASW perception.

physical measures for ASW.[11-18] DICC and DICC (1600) are useful for ASW for a typical orchestral music and a wide band noise which contains low frequency components, respectively. Namely, their applications are limited. For example, they can not be applied to the source signals consisting of only high frequency components above 1.6 kHz.

The purpose of this study is to establish a prediction method which can estimate ASW quantitatively for any source signal and any sound field. The authors have presented a technical prediction model of ASW.[14] According to this model, ASW for input signals to both ears can be estimated by summing up 1/3 octave band ASW multiplied by the weighting factor W. In this paper, the psychological experiments of ASW were performed to examine the validity of the model under the very fundamental condition that the number of adjacent 1/3 octave bands was two and each band had an identical sound pressure level.

2. TECHNICAL PREDICTION MODEL OF ASW

In the previous paper,[14] a functional model of *ASW* perception was formulated from the results of the psychological experiments, as shown in Fig. 1. The input signals to both ears are analyzed through the critical band filters, and the degree of interaural cross correlation and the sound pressure level of each critical band (ρ_i and L_i) are obtained. ρ_i and L_i change to ρ_i' and L_i', respectively, due to interactions between the bands. ASW for each critical band (ASW_i) is obtained from ρ_i' and L_i'. Again, ASW_i changes to ASW_i' due to interactions between the bands. Finally, total ASW for over all frequencies ($ASW_{O.A.}$) is perceived as the sum of ASW_i'. This model takes into account three interactions, namely the interaction of ρ_i, L_i and ASW_i, though it is not clear whether they exist or not. To estimate ASW quantitatively using this model, it is necessary to individually define the quantitative effects of these interactions on ASW. It is, however, impossible. ASW is finally perceived for a single fused sound image, so that the effects of these interactions on ASW can not be observed separately.

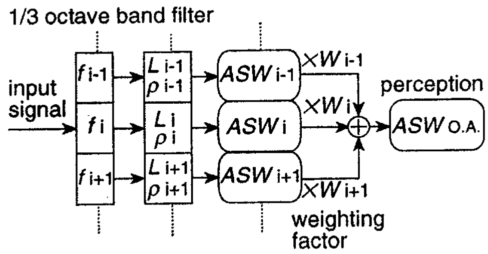

Fig. 2 Technical prediction model of ASW.

Therefore, a technical prediction model of ASW has been formulated, as shown in Fig. 2, based on the functional model of ASW perception. The input signals to both ears are analyzed through the 1/3 octave band filters, and the degree of interaural cross correlation and the sound pressure level of each 1/3 octave band (ρ_i and L_i) are calculated. From ρ_i and L_i, 1/3 octave ASW (ASW_i) is obtained. Finally, $ASW_{O.A.}$ is estimated by summing up ASW_i multiplied by the weighing factor for each 1/3 octave band (W_i). In this model, the 1/3 octave band filters are considered to correspond to the critical band filters. Moreover, the three interactions are described simply as the weighting factor W_i which is a function of ρ_i, L_i, and the frequency band f_i. This model is expressed as

$$ASW_{O.A.} = \sum ASW_i \times W_i \qquad (1)$$

In order to estimate ASW quantitatively using this model, weighting factor W_i and the quantitative relations between ASW_i and physical measures, ρ_i and L_i, are necessary.

3. EXPERIMENT

In the most past studies, ASW was evaluated in relative values, that is "which was wider or narrower". It is impossible, however, to examine the validity of the model from the results of the relative evaluation of ASW. In this experiment, the quantitative judgments of ASW for two adjacent 1/3 octave band noises were performed.

3.1 Method of Quantitative Judgment of ASW

Seventy-two light-emitting diodes (LED) were arranged every 2.5 degrees in the frontal semicircle of a subject on the horizontal plane including his aural axis, as shown in Fig. 3. 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. The subject was required to adjust the position of the shining LED at the both horizontal ends of "the area where he felt the sound existed". The angle of the degree between the two shining LED was regarded as the quantitative scale of ASW.

3.2 Subject

Subjects were three male and one female students, with normal hearing sensitivity. They practiced the quantitative judgment of ASW many times before the experiment.

3.3 Stimuli and Apparatus

The stimuli were three kinds of 2/3 octave band noise; (500 Hz+630 Hz; 2/3 octave band noise composed by two adjacent 1/3 octave band noises whose center frequencies are 500 Hz and 630 Hz, respectively), (800 Hz+1 kHz), and (4 kHz+5 kHz), and six kinds of 1/3 octave band noise which compose the three kinds of 2/3 octave band noise.

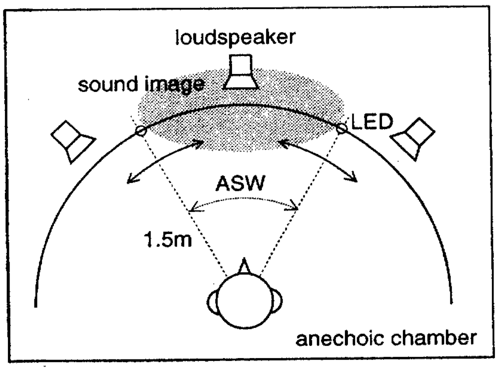

Fig. 3 Method of quantitative judgment of ASW.

First, the four steps of the degree of interaural cross correlation were set for each 1/3 octave band. The degrees of interaural cross correlation of the steps were set from the results of the preliminary tests and they were decided to be distinguishable with regard to ASW. Therefore, they depend on the subject and the centre frequency of 1/3 octave band. Secondly, the 2/3 octave band noises were made by combining the two adjacent 1/3 octave band noises. Because there were four steps for each 1/3 octabe band noise, the sixteen combinations of the degree of interaural cross correlation were obtained for each 2/3 octave band. The 1/3 octave band level was constant at 65 dB and the 2/3 octave band level was constant at 68 dB. They were measured at the left ear of KEMAR dummy head.

The stimuli were radiated from three cylindrical loudspeakers. The first loudspeaker was 1.5 m in front of the subject. The other two loudspeakers were located at an azimuth of $\pm\alpha°$, also at a distance of 1.5 m. The three loudspeakers radiated incoherent noise signals. The degree of interaural cross correlation of the stimuli were adjusted by controlling the ratio of lateral to frontal energy. The azimuth α depends on the center frequency of 1/3 octave band noise so that the degree of interaural cross correlation could be changed to be distinguished with regard to ASW without split sound images. The azimuth α are 90°, 60° and 15° for (500 Hz, 630 Hz), (800 Hz, 1 kHz), and (4 kHz, 5 kHz), respectively.

3.4 Procedure

The experiment was carried out separately for each 2/3 octave band in a darkened anechoic chamber. Each subject was individually tested while seated, head fixed. For each 2/3 octave band, the stimuli of the 1/3 octave band noises and the 2/3 octave band noises were presented in random order and the subjects judged ASW of the stimuli quantitatively. The stimulus was presented continuously until the subject finished his task. Each subject made six judgments for each stimulus in total.

4. RESULTS AND DISCUSSION

All subjects perceived a single fused sound image for the most stimuli. The judgments for the stimuli perceived as split sound images were excluded from the analysis (about 8% of all responses).

4.1 ASW for 1/3 Octave Band Noises

Figures 4(a)-(c) show the average ASW for each 1/3 octave band noise as a function of the degree of interaural cross correlation. The results of the different subjects are indicated in the different panels. The vertical bars at the symbols indicate the standard deviations of ASW judgments. The standard deviations of ASW range from 0° to about 30° and the mean value is 6.8°. This value is less than that in the past works[8,13] where the mean values of the standard deviation are about 20°, and this means that there is high reliability of the subject's judgments in the experiment.

All results show a common feature. For any 1/3 octave band noise, ASW decreases monotonously as the degree of interaural cross correlation grows. This tendency coincides with the well-known relationship between ASW and the degree of interaural cross correlation, as mentioned in the introduction. Furthermore, ASW for 500 Hz and 630 Hz (Fig. 4(a)) are wider than those for the other 1/3 octave band noises except subject A.

4.2 Validity of the Technical Prediction Model of ASW

The multiple regression analysis was applied to

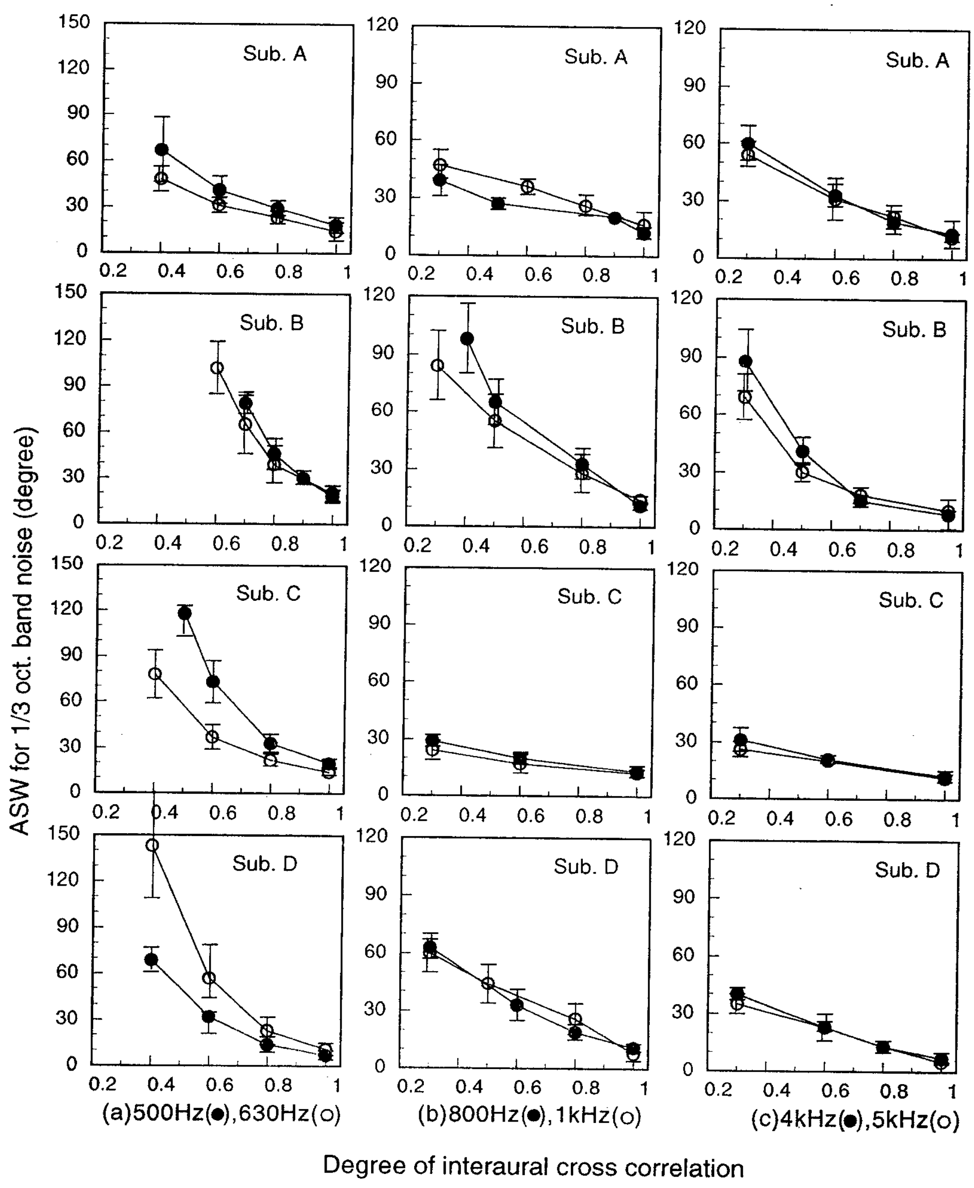

Fig. 4 ASW for 1/3 oct. band noise. (a), 500 Hz and 630 Hz; (b), 800 Hz and 1 kHz; (c), 4 kHz and 5 kHz.

examine the validity of the technical prediction model of ASW. That is to say, it was investigated whether or not ASW for a 2/3 octave band noise could be estimated from ASW for two 1/3 octave band noises composing the 2/3 octave band noise using the linear regression function. The criterion variable was ASW for the 2/3 octave band noise, and the predictor variables were the average ASW for the 1/3 octave band noises.

Table 1 shows the results of the multiple regression analysis. The multiple correlation coefficients are more than 0.7 in all cases and more than 0.8 in nine out of twelve cases. Further, the constants of the equations are negligible except for (800+1 k) of subject B, because their absolute values are comparable to the average of the standard deviations of the judgments, that is 6.8°. Figure 5 shows the relationship between perceived and estimated ASW for (4 kHz+5 kHz) as an example. Estimated ASW was calculated from average ASW for 1/3 octave band noises by use of the linear regression functions shown in Table 1. The different panels show the results of the different subjects. If plural plots are at the same position, they are plotted as only one circle. For all subjects, the plots scatter along the diagonal line over the wide range of ASW and good correlation between perceived and estimated ASW is observed. A similar tendency can be

Table 1 Results of multiple regression analysis.

Stimulus	Subject	Equation of multiple regression*a	rr*b
(500+630)	A	$Y=0.53X_1+0.49X_2+5.49$	0.78
	B	$Y=1.12X_1+0.54X_2-5.00$	0.86
	C	$Y=1.42X_1+0.44X_2-9.5$	0.94
	D	$Y=1.45X_1+0.46X_2-9.5$	0.94
(800+1 k)	A	$Y=0.46X_1+0.49X_2+3.73$	0.81
	B	$Y=1.00X_1+0.88X_2+29.43$	0.73
	C	$Y=0.37X_1+0.64X_2+3.19$	0.71
	D	$Y=0.20X_1+0.85X_2+7.51$	0.87
(4 k+5 k)	A	$Y=0.48X_1+0.58X_2+3.70$	0.89
	B	$Y=0.52X_1+0.72X_2-1.30$	0.88
	C	$Y=0.50X_1+0.47X_2+3.38$	0.81
	D	$Y=0.53X_1+0.38X_2+1.16$	0.87

*a Y is ASW for 2/3 oct. band noise. X_1 is ASW for lower 1/3 oct. band noise. X_2 is ASW for higher 1/3 oct. band noise.
*b rr is multiple correlation coefficient.

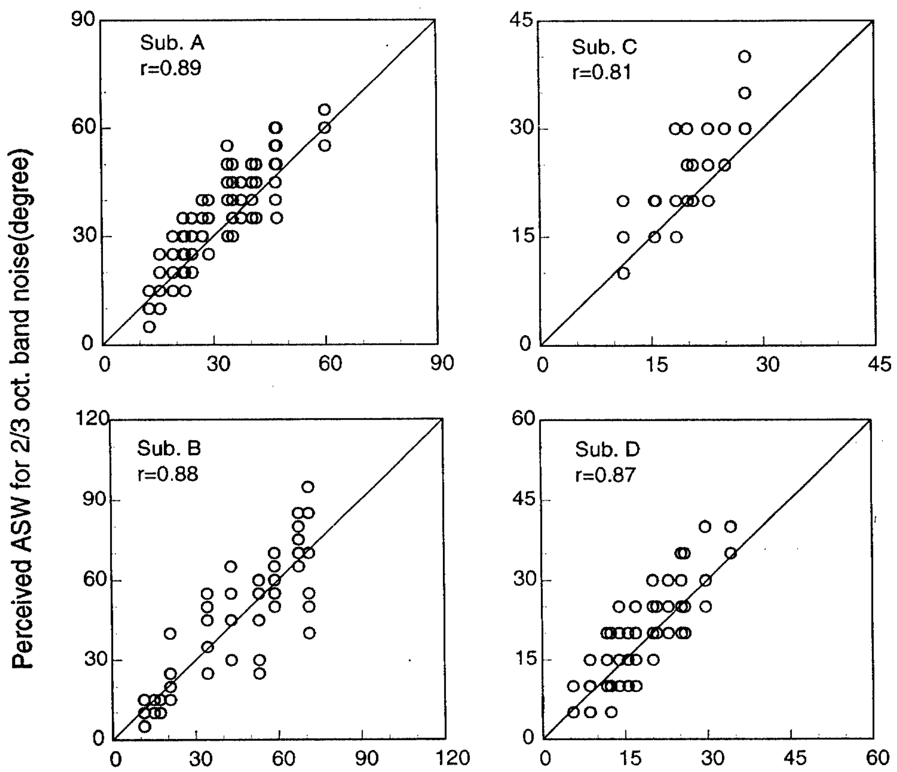

Fig. 5 Relation between perceived and estimated ASW for (4 kHz+5 kHz).

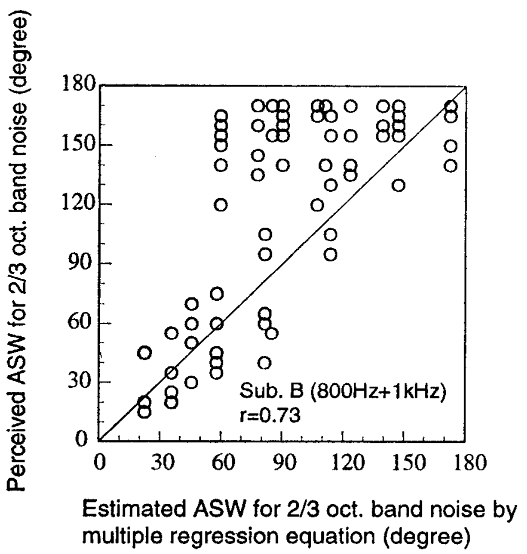

Fig. 6 Relation between perceived and estimated ASW for (800 Hz+1 kHz) of subject B.

seen for (500 Hz+630 Hz) and (800 Hz+1 kHz) except for (800 Hz+1 kHz) of subject B. These results prove the validity of the technical prediction model of ASW. In other words, it becomes clear that ASW for a 2/3 octave band noise can be estimated by adding two ASW for each 1/3 octave band noise multiplied by the weighting factor W.

Figure 6 shows the relationship between perceived and estimated ASW for (800 Hz+1 kHz) of subject B. It is quite different from Fig. 5. For the estimated ASW in the range of 0° to 60°, the good correlation to observed between perceived and estimated ASW. For the estimated ASW over 60°, the perceived ASW agree with the estimated ASW for some stimuli, however many stimuli are perceived over 150° regardless of the estimated ASW. Moreover, for only this 2/3 octave band, subject B reported that he perceived some stimuli close to his ears and it was difficult for him to judge ASW. From these facts, the judgment of subject B for (800 Hz+1 kHz) are regarded as being less reliable though the multiple correlation coefficient is high.

4.3 Weighting Factor

The regression coefficients of X_1 and X_2 shown in Table 1 are regarded as the weighting factor W. The weighting factor W of each 1/3 octave band is shown in Table 2, again. W for 800 Hz and 1 kHz of subject B are enclosed in the parentheses and they are except from the following consideration, because these values are less reliable as mentioned in the Sec. 4.2. For subject A, W is about 0.5 for all 1/3 octave bands. For the other three subjects, however, W depends on the centre frequency of 1/3 octave band and the subject as follows: For (500 Hz+630 Hz), W for 500 Hz is larger than those for 630 Hz. For (800 Hz+1 kHz), W for 800 Hz is smaller than W for 1 kHz, however the differences are less than those for (500 Hz+630 Hz). For (4 kHz+5 kHz), W is about 0.5 for both 1/3 octave bands. Roughly speaking, W is about 1.0 or more for 500 Hz and about 0.5 for the other 1/3 octave bands under the given condition.

Table 2 Weighting factor of each 1/3 oct. band.

Subject	Weighting factor W					
	500 Hz	630 Hz	800 Hz	1 kHz	4 kHz	5 kHz
A	0.53	0.49	0.46	0.49	0.48	0.58
B	1.12	0.54	(1.00)	(0.88)	0.52	0.72
C	1.42	0.44	0.37	0.64	0.50	0.47
D	1.45	0.46	0.20	0.85	0.53	0.38

The parenthesis means that the value is regarded as being less reliable.

As mentioned in Sec. 2, the weighting factor W is assumed to be functions of the sound pressure level of each 1/3 octave band (L_i), the degree of interaural cross correlation of each 1/3 octave band (ρ_i), and the frequency band (f_i). In this experiment, ρ_i and f_i were changed. The results showed that weighting factor W depended on f_i. On the other hand, it was implied that ρ_i had little influence on W. According to the results of the multiple regression analysis, the multiple correlation coefficients rr in Table 1 are high in spite of ASW for the 2/3 octave band noises with different combinations of ρ_i are adopted in the analysis. If W depend on ρ_i, W should also depend on the combination of ρ_i and, as a result, multiple correlation coefficient rr, shown in Table 1, should become low.

5. CONCLUSION

The validity of the technical prediction model of auditory source width (ASW) was examined using two adjacent 1/3 octave band noises as stimuli. The results of the quantitative judgments of ASW indicate that: (1) The technical prediction model of ASW is valid. Namely, ASW for 2/3 octave band noise can be estimated by summing up ASW for 1/3 octave band noises multiplied by the weighting factor W. (2) The weighting factor W depends on the frequency band and the subject. Roughly speaking, W for 500 Hz is larger than those for the other frequencies under the given condition.

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