DIFFERENCE LIMENS FOR MEASURES OF APPARENT SOURCE WIDTH

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ABSTRACT

Apparent source width (ASW) is thought of being one important component of spatial impression in concert halls. The validity of known objective measures that correlate with ASW, namely LF_{E4} and $IACC_{E3}$, has recently been questioned as measurements of these quantities in concert halls revealed significant fluctuations over small spatial intervals. In a first step towards assessing the perceptual relevance of these fluctuations, listening tests aimed at finding a threshold difference below which changes in perceived ASW are no longer relevant for concert halls were carried out. The results of these tests are discussed together with implications for further research.

1 INTRODUCTION

Apparent source width (ASW) is thought of being one important component of spatial impression in concert halls. As spatial impression is considered a major acoustical attribute of halls, it should be taken into account in the design of new, or in the modification of existing, halls. In order to aid the design process, objective measures (i.e. quantities that can be measured in existing halls or models of halls) have been developed.

In the case of ASW, these objective measures include the strength factor at low frequencies, as well as the early parts of the lateral fraction, the interaural cross-correlation coefficient (all of which are defined in the appendix to ISO 3382 [1]) and that of TRAUTMANN's criterion RL [2]. All of these measures, with perhaps the exception of the strength factor, are subject of ongoing discussions [1, 3, 2, 4].

One major point of criticism is that these measures can fluctuate considerably over small spatial intervals (one and the same seat), both in concert halls [5] and in virtual sound fields [6]. Whereas most people argue that one will usually not perceive differences in ASW over one and the same seat, it was recently shown that one can create pairs of plausible virtual sound fields whose differences in ASW are judged differently when the subjects lean towards the left or the right side of the seat [6].

To aid future investigations into this field, it would be helpful to have difference limens for the known objective measures, i.e. differences below which no change in ASW is perceived. On the other hand, investigations into difference limens must take into account that, even in a listening experiment with well controlled parameters, there may be fluctuations of the objective measures depending on the actual position of the subject's head. This latter fact appears to be completely ignored in the work on difference limens for objective measures published so far.

In the work presented here, investigations on difference limens for measures of ASW were carried out with special attention paid to spatial variations of the measure in question.

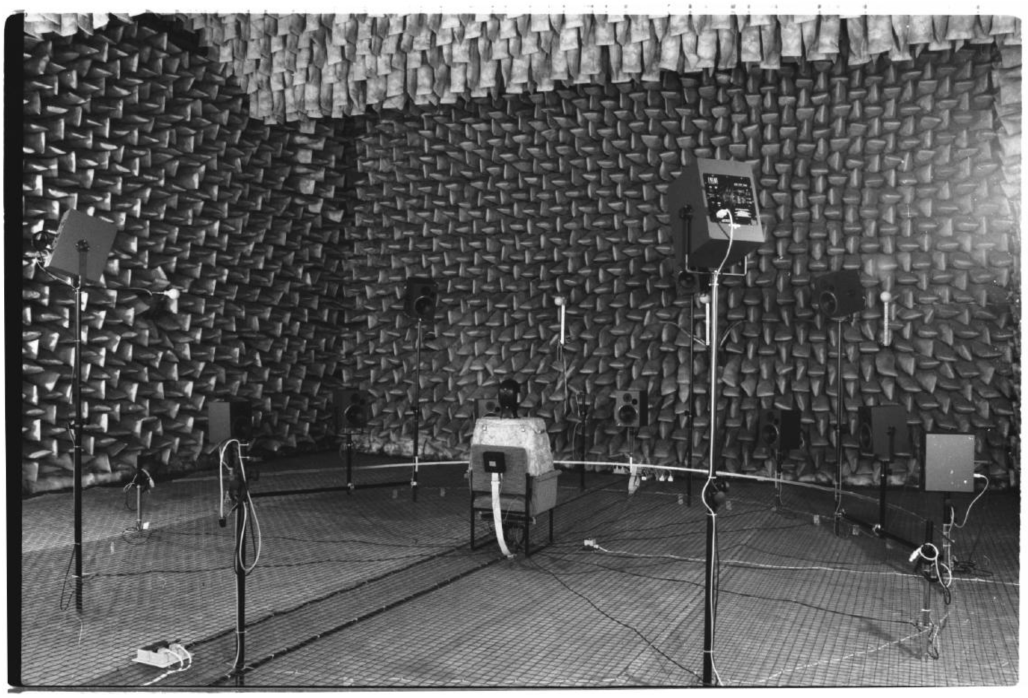

Figure 1: Listening test: set-up.

2 LISTENING TESTS: METHOD

Listening tests were carried out in the anechoic room of Institut für Akustik und Sprachkommunikation (room free volume: 1000m^3, low-frequency limit: 60Hz). The test set-up is shown in fig. 1. Subjects were seated in the center of a circular louspeaker array (radius 3m) which served to produce virtual sound fields based on anechoic music (a continuous repetition of bars 560/561 of the first movement of the Symphony No. 4 in E-flat by BRUCKNER, taken from the CD "Anechoic Orchestral Recordings" by DENON). All experiments were carried out in the dark in order to exclude visual cues. The virtual sound fields consisted of the direct sound (originating from the loudspeaker in front of the subject) plus eight reflections with varying level and delay (delivered by loudspeakers at ±30°, ±45°, ±60°, ±85°, respectively). The sound fields were generated randomly by imposing the following conditions:

1. the larger the angle of incidence, the larger the delay,
2. reflections with symmetric angles of incidence were required to be at least 3ms apart,
3. reflection levels were chosen from a modified χ^2-distribution with given mean and maximum values which in turn were varied but always decreased with increasing delays,
4. the total energy of the reflection was adjusted such that it was within 0.5dB of that of the direct sound.

Eight sound fields were finally chosen by subjective evaluation. They are summarized in table 1.

Eight trained subjects (sound engineers, musicians, acousticians) with experience in listening tests took part in the experiments. A modified pair-comparison paradigm (see [7]) was used: For each pair comparison, subjects could in a first step deliberately switch between the two sound fields (transition time: 10ms) until they figured out the one they thought had the larger ASW. In a second step, they were asked to rate the difference in ASW between the two sound fields on a scale from 1 (no difference) to 5 (a clear difference). Subjects were instructed to pay attention to ASW as a fused impression (they were told that all loudspeakers did contribute to any field). The meaning of the scale was defined as: 1 (no difference) – no difference in ASW, 3 (a small difference) – "I can hear a difference in ASW but it takes some concentration to be sure", 5 (a clear difference) – "I can hear a difference in ASW without much effort". In the subsequent analysis,

	0°	-30°	+30°	-45°	+45°	-60°	+60°	-85°	+85°
TSF 1	0ms	25.5ms	32.8ms	42.8ms	36.0ms	52.1ms	63.5ms	73.6ms	49.0ms
	0dB	-13.9dB	-16.3dB	-8.1dB	-6.7dB	-9.1dB	-7.2dB	-10.7dB	-12.3dB
TSF 2	0ms	31.7ms	26.4ms	40.9ms	44.7ms	37.1ms	60.3ms	51.5ms	68.4ms
	0dB	-13.9dB	-20.5dB	-7.7dB	-8.5dB	-7.3dB	-8.6dB	-9.1dB	-10.7dB
TSF 3	0ms	28.0ms	31.2ms	48.9ms	41.0ms	44.9ms	37.5ms	57.2ms	74.3ms
	0dB	-9.9dB	-7.3 dB	-13.7dB	-9.8 dB	-6.2 dB	-7.9 dB	-24.1dB	-13.3dB
TSF 4	0ms	25.5ms	32.8ms	42.8ms	36.0ms	52.1ms	63.5ms	73.6ms	49.0ms
	0dB	-6.0dB	-10.1dB	-7.9 dB	-10.4dB	-11.4dB	-8.9 dB	-13.8dB	-13.3dB
TSF 5	0ms	21.9ms	37.2ms	43.9ms	26.7ms	48.9ms	59.8ms	76.3ms	54.5ms
	0dB	-8.1dB	-9.3 dB	-8.6 dB	-11.8dB	-6.8 dB	-9.2 dB	-11.2dB	-18.7dB
TSF 6	0ms	15.1ms	24.8ms	37.9ms	28.8ms	58.7ms	47.5ms	75.1ms	52.4ms
	0dB	-7.1dB	-9.3 dB	-6.1 dB	-14.1dB	-10.6dB	-10.7dB	-11.0dB	-13.7dB
TSF 7	0ms	25.8ms	38.6ms	47.9ms	31.6ms	62.6ms	53.5ms	73.2ms	58.4ms
	0dB	-5.4dB	-5.5 dB	-10.5dB	-15.4dB	-10.3dB	-11.2dB	-17.0dB	-19.5dB
TSF 8	0ms	25.7ms	32.8ms	45.8ms	52.7ms	56.4ms	60.1ms	72.8ms	69.8ms
	0dB	-5.0dB	-5.3 dB	-11.9dB	-14.6dB	-16.2dB	-11.9dB	-12.8dB	-18.2dB

Table 1: Listening test: Parameters of the eight test sound fields. Given are delays and levels for reflections arriving under the indicated angles of incidence.

the absolute value of the scale values was decreased by 0.5 in order to rejoin positive and negative scales after the enforced split in the first step. As complete sets of pair-comparisons were tested, the consistency of the judgements could be verified: All subjects achieved a coefficient of consistency of at least 0.8. Each session lasted about 30min.

All signal processing and the test control was provided by a Personal Computer running jMax 2.5.1 (IRCAM), equipped with a 16-channel audio interface (RME Digi9632 + Creamware A16). Objective measures were calculated on the basis of measured binaural impulse responses (artificial head: Neumann KU-80). As the calculation of RL_E involves the determination of the sine of incidence angles of 2ms long sections of the first 80ms of the binaural impulse response, one can derive a modified lateral energy fraction LFC'_E from it,

$$LFC'_E = \frac{\sum_{i=1}^{W} E_i \sin\varphi_i}{E_D + \sum_{i=1}^{W} E_i}. \tag{1}$$

In this equation, E_i and φ_i are the energy and the angle of incidence of the ith section of the binaural impulse response and E_D is the energy of the direct sound. Because of the directional characteristics of the artificial head, values of LFC'_E are different from (higher than) what would be measured with the classical combination of figure-of-eight and omnidirectional microphones. However, both are highly correlated, with LFC'_{E4} being about 2.4 times LF_{E4} for the sound fields studied here.

Although the position of the subject's head was predetermined to a certain degree by the seat, it was not explicitely enforced to be the same for all subjects. Therefore, the impulse responses were measured on a grid of 8×8cm (every 2cm) in the head plane.

In addition to the octave-band averaged values of $IACC_E$, RL_E and LFC'_E (i.e. $IACC_{E3}$, RL_{E6} and LFC'_{E4}, with $E3$: 500Hz…2kHz, $E4$: 125Hz…1kHz, $E6$: 125Hz…4kHz), broadband versions based on low-pass (at 6kHz) filtered impulse responses were considered as well. These measures are referred to as $IACC_{Ebb}$, RL_{Ebb} and LFC'_{Ebb}, respectively. Measured values ranged from 0.42 to 0.30 ($IACC_E$), -3.8dB to 0.7dB (RL_E) and from 0.38 to 0.62 (LFC'_E).

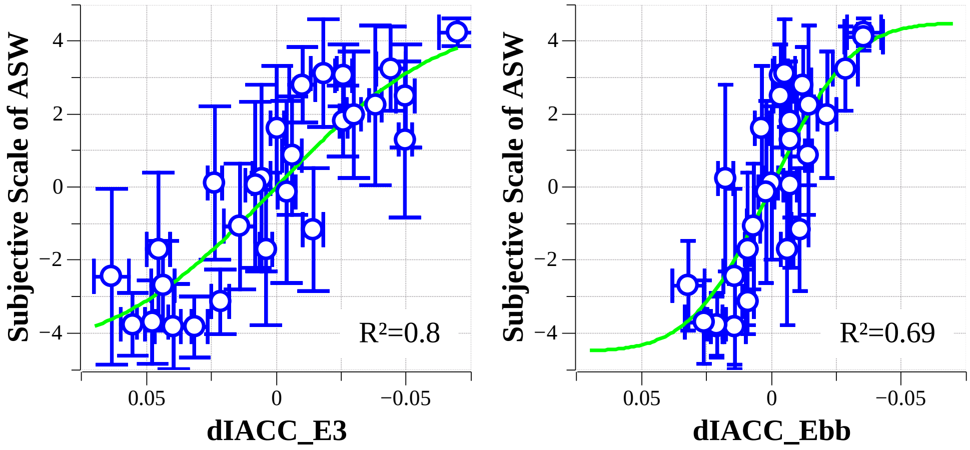

Figure 2: Listening test: subjective judgements of ASW versus differences in $IACC_E$. Circles represent means, vertical error bars 95% confidence intervals for the mean of the judgements, horizontal error bars 95% confidence intervals for the mean of the difference in $IACC_E$. The solid curve is the model for the means, according to eq. 2. **Left:** $IACC_{E3}$. **Right:** $IACC_{Ebb}$.

3 LISTENING TESTS: RESULTS

In fig. 2, subjective scale values for individual test pairs are plotted versus the differences in $IACC_E$. For both versions of the $IACC_E$, the correlation between judgements and objective measures is fairly good. However, for the broad-band version the change in the judgements is much larger for a given difference in $IACC_E$. Conversely, the values (and the differences) of the $IACC_{Ebb}$ are within much smaller limits than those of the $IACC_{E3}$.

An inspection of the confidence intervals for the means of both the subjective judgements and the difference in $IACC_E$ suggests that the influence of spatial variations in $IACC_E$ over the area where the subjects' heads were, is not very important (compared to that of the fluctuations in the subjective judgements).

The appearance of the relation between subjective scale values and differences in the objective measure suggests that a linear model with saturation for large absolute differences in $IACC_E$ could be used. The model adopted here is a modified error integral,

$$\text{mean judgement} = \begin{cases} \frac{9}{\sqrt{\pi}} \int_0^{|\mathrm{d}IACC_E|} \mathrm{e}^{(\xi/\sigma)^2}\, \mathrm{d}\xi & \text{if } \mathrm{d}IACC_E \leq 0 \\ -\frac{9}{\sqrt{\pi}} \int_0^{|\mathrm{d}IACC_E|} \mathrm{e}^{(\xi/\sigma)^2}\, \mathrm{d}\xi & \text{if } \mathrm{d}IACC_E > 0 \end{cases} . \qquad (2)$$

This model was iteratively (in σ) fitted to the means of both the subjective judgements and the differences in $IACC_E$.

Similar analyses were carried out for RL_E and LFC'_E, see figs. 3 and 4. In comparison to $IACC_E$, the correlation between judgements and objective measures is not as good, and differences between octave-band averaged and broad-band versions of the measures are negligeable.

4 DISCUSSION

In the preceding section, results of listening tests were presented in the form of subjective scale values of differences in ASW, as a function of differences in the objective measures. To derive difference limens from these relations, Höhne and Schroth [7] proposed to consider the value of the objective measure at which the value of the model function is ±2.5. This means that the average (experienced) listener will perceive a small difference in ASW, under ideal listening conditions and in a pair-comparison scenario. It is the author's belief that this proposal is a sensible criterion for the difference limen, if different seats in a hall are to be compared.

Following this proposal, the difference limen for the $IACC_{E3}$ would turn out to be 0.038, and that of the $IACC_{Ebb}$ 0.019. For RL_E it would be 1.8dB, and for LFC'_E 0.11.

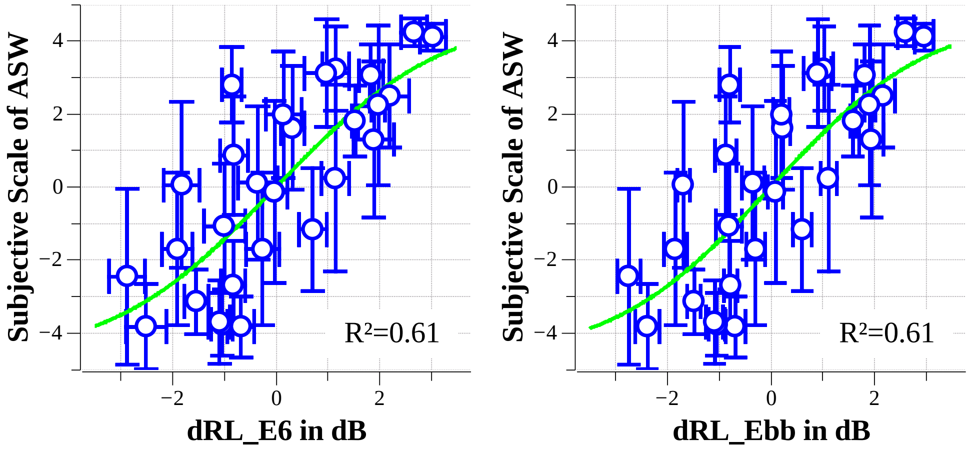

Figure 3: Listening test: subjective judgements of ASW versus differences in RL_E. Circles represent means, vertical error bars 95% confidence intervals for the mean of the judgements, horizontal error bars 95% confidence intervals for the mean of the difference in RL_E. The solid curve is the model for the means, according to eq. 2 (where d$IACC_E$ must be substituted by $-$dRL_E). **Left:** RL_{E6}. **Right:** RL_{Ebb}.

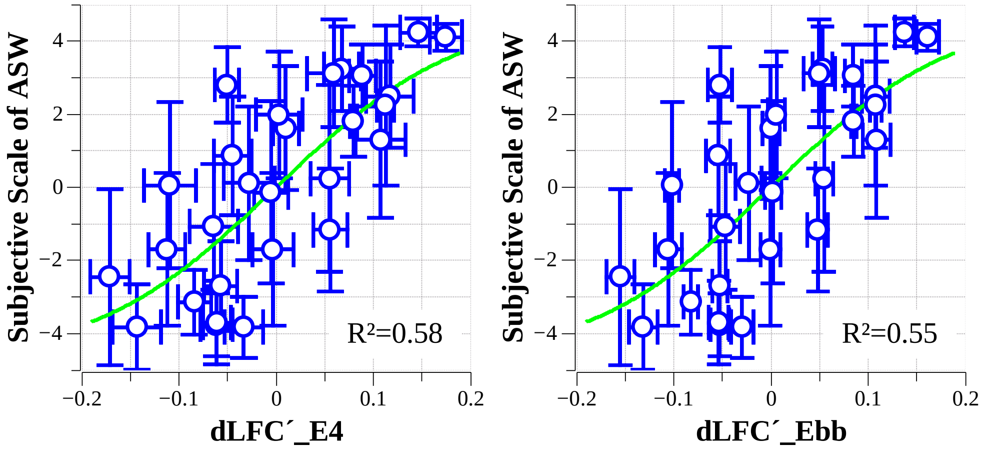

Figure 4: Listening test: subjective judgements of ASW versus differences in LFC'_E. Circles represent means, vertical error bars 95% confidence intervals for the mean of the judgements, horizontal error bars 95% confidence intervals for the mean of the difference in LFC'_E. The solid curve is the model for the means, according to eq. 2 (where d$IACC_E$ must be substituted by $-$dLFC'_E). **Left:** LFC'_{E4}. **Right:** LFC'_{Ebb}.

If the difference limen for LF_{E4} is estimated from that of LFC'_{E4} (using the factor 2.4 mentioned in section 2) or from that of the $IACC_{E3}$ (using a logarithmic model of data by BERANEK [8]), a value of 0.045. . . 0.07 is obtained.

The difference limen for the $IACC_{E3}$ found here is somewhat lower than the values found recently by OKANO [4] (0.05. . . 0.07) or that found by COX et al. for the $IACC_{E4}$ [9] (0.075). The most likely reason for this (small) discrepancy is that in those investigations, only the level of one or more reflections was altered whereas in the work presented here, completely different sound fields were compared. A relatively low difference limen for $IACC_E$ is however consistent with results from investigations on the perception of spatial fluctuations of the $IACC$ [6].

As was seen in section 3, the $IACC_E$ gave the best correlation with the subjective judgements in the tests presented here. However, previous investigations [2, 10] have shown that this is not consistently the case. Instead, the $IACC_E$ sometimes produced predictions which largely underestimated the subjective judgements. Future work is needed to clarify this issue.

Also, the work presented here should be extended to different ranges of the objective measures.

5 CONCLUSION

In this paper, investigations aiming at finding difference limens for measures of apparent source width (ASW) were presented. As opposed to work published so far, spatial fluctuations over the area of the subjects' head of the objective measure in question were controlled, and a pair comparison technique in which both level and delays of all reflections were altered was used.

Using a criterion proposed by HÖHNE and SCHROTH, the difference limen for the $IACC_{E3}$ was found to be 0.038, for values of the $IACC_{E3}$ between 0.3 and 0.42. For the corresponding value of RL_{E6} between -3.8dB and +0.7dB, the difference limen was found to be 1.8dB. The difference limen for LF_{E4} can be estimated from the difference limen of the $IACC_{E3}$ and from that of LFC'_{E4}. For a value of the LF_{E4} between 0.18 and 0.26, this estimate is 0.045. . . 0.07.

Future work is needed to cover other ranges of the objective measures and to clarify the origin of some outliers that the $IACC_E$ produced in previous listening tests.

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