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Audience noise in concert halls during musical performances

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In the acoustic design of performance spaces, the specifications for background noise levels are set very low. However, noise generated by the audience is not taken into account. In this study, a method has been developed for determining the noise produced by the audience during a performance. From the recordings of performances in five performance spaces (four concert halls and one opera house), probability density functions of the sound pressure levels were obtained. The noise produced by the audience is identified from it. Empirical prediction models were made using the four concert halls, revealing that the audience noise level is significantly correlated with the technical background noise level. It is therefore concluded that a relaxation of the current background noise recommendations for concert halls is not recommended.

1 INTRODUCTION

Background noise is one of the crucial acoustical concerns when planning concert halls or opera houses. However, existing design criteria for the background noise due to technical installations in performance spaces have been developed without regard to the noise generated by an audience.

Many countries have regulations for general and public buildings, stated in A-weighted decibel scales or in terms of room noise criteria defined by a set of empirical reference curves, e.g., the Noise Criterion (NC) curves, the Balanced Noise Criterion (NCB), and the Room Criterion (RC) curves. These methods are widely used in the design of concert halls. A selection of design guidelines for background noise in concert halls and opera houses using NC, NCB, and

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RC curves is listed by Jeong et al..[1] Strangely there is no uniformity in the results, not even between recommendations by the same author. However, no matter which noise criteria are used, a rating of less than 20 should be achieved.

There have been increasing demands for lower technical background levels in newly built halls. However, none of the concerned authors have examined how silent an audience of, say, 2000 persons can be.

By contrast, the human activity noise is not well understood, although it obviously has an influence on the audibility of the technical noise. A recent investigation of noise generated by students during lectures in university classrooms was carried out by Hodgson et al. and led to an empirical model for the student activity noise.[2]

As an incipient attempt, this study addresses a method for extracting the audience noise, applied in five southern Scandinavian performance halls. Finally, the obtained audience noise was analyzed statistically and modeled empirically.

2 METHOD

A typical concert consists of orchestra sound in the presence of a relatively low noise. The noise can be divided into two groups: the noise generated by technical installations, called the "technical background noise," and the noise due to people's activity referred to as the "audience noise." Note that the audience noise does not include noise during intermissions. Since both noise components exist concurrently, both are mixed in recorded signals during a performance, being named the "mixed background noise."

However, because recordings of a musical performance are comprised of a musical signal and mixed background noise, an appropriate method should be used to extract the mixed background noise. The method suggested by Hodgson et al. [2] to estimate students' activity noise during lectures was modified to extract the mixed background noise from orchestra/singer/soloist sound.

2.1 Measurements

The five halls investigated: Five performance halls have been used to extract the audience noise. They can accommodate 408 to 1500 people. All the measurements were done between 2009 and 2010. The halls were fully occupied during the recordings. Four to five measurement points were spread over the audience, one microphone being always installed at the conductor's position. Important information about the halls is given in Table I. More detailed information about the halls can be found in Jeong et al.. [1]

Equipment used: Two types of low noise microphones, a 1" microphone (B&K type 4145) and a [1/2]" microphone (B&K type 4165) connected to a B&K amplifier Nexus 2690 are used for the measurement. The signals are recorded as WAV files with a sampling rate of 44.1 kHz and the recorder had a dynamic range of 24 bit (approximately 144 dB).

During performance measurements: The recordings had started before the main concerts started, and the recorded signals were checked over during intermissions by visual inspection of the displays of the signal conditioners and the recorder. Calibration signals were recorded before and after the measurements for all the channels.

Measurement of room acoustic parameters: After the performances had ended, room acoustic parameters and the technical background noise were measured in an empty condition at the same microphone positions as during the performance.

2.2 Extraction of the probability density function from a time history

The recorded wave files, which are 2–3 hours long, were divided into short segments, each of which was 100 ms long. For each temporal segmentation, a frequency analysis was applied to calculate the equivalent sound pressure levels in octave bands centered from 63 Hz to 8 kHz over the given time period. As a result, a number of equivalent levels were obtained for each octave band, which were used for obtaining probability distributions of the sound pressure level in the frequency bands of interest.

Figure 1(a) shows an imaginary but typical time history example of a recorded signal, showing louder musical sound and quieter mixed background noise. The mixed background noise exists all the time, but it is masked by the musical sound when played. From the time history, probability distributions of the sound pressure level in octave bands were found. A probability density function in Fig. 1(b) shows two peaks, the large and small peak, which correspond to the musical sound and the mixed background noise distribution, respectively. L_{90} of the mixed noise, the noise level exceeded for 90% of the measurement time, is indicated to explain its meaning. The abscissa is the sound pressure level in dB, which is the short time equivalent sound level. The ordinate indicates a fraction of the played to the total measurement time. The area under the probability density function should be unity. Note that the probability density functions were obtained in eight octave bands for each microphone position.

2.3 Regression of probability density functions

In the recorded performances, there exist three components, orchestra sound, singer voice or soloist sound, and mixed background noise. They can be separated by a fitting process under the following assumptions: they are individual acoustical events, they each follow a Gaussian distribution and they are independent of each other. The probability density function of the recorded signal can therefore be regressed as a weighted sum of these independent Gaussian distributions, $p_{\mu,\sigma}$ (where μ is the mean value, and σ the standard deviation) in which the distribution with the lowest mean corresponds to the mixed background noise. A probability density function model will be given by:

$$p_m(L_i|\mathbf{I}) = A_1 \cdot p_{\mu_1,\sigma_1}(x_1) + \mathrm{A}_2 \cdot p_{\mu_2,\sigma_2}(x_1) + (1 - A_1 - A_2) \cdot p_{\mu_3,\sigma_3}(x_1) \qquad (1)$$

where $\mathbf{I} = \{A_1, A_2, \mu_1, \mu_2, \mu_3, \sigma_1, \sigma_2, \sigma_3\}$, A_i, μ_i, σ_i are the i^{th} weighting, mean, and standard deviation, respectively. Note that A_i is always positive and less than unity. Then the residual sum of squares (RSS) was defined as an error function as follows:

$$RSS(\mathbf{I}) = \sum_i^n \varepsilon_\mathrm{i}^2 \qquad (2)$$

where $\varepsilon_i = p_e(L_i) - p_m(L_i|\mathbf{I})$, p_e is the measured probability density function. Since the probability density function is calculated with a step of 1 dB, n is L_{max}-L_{min}+1. For minimization of the error function, a function “fminsearch” in MATLAB was used, which is an unconstrained nonlinear optimization method.

The main purpose of this fitting process is to identify the mixed background noise. The mixed background noise is likely to have a mean around 30 dB. Therefore a modified error function is defined by weighting the RSS below 40 dB and counterweighting the RSS higher than 60 dB. The weightings used were $\sqrt{50}$ and $\sqrt{5}$ for levels below 40 dB and beyond 60 dB, respectively, and accordingly the weighted RSS is rewritten as:

$$RSS_w = \sqrt{50} \sum_i^{40-L_{min}+1} \varepsilon_\mathrm{i}^2 + \sum_{40-L_{min}+2}^{60-L_{min}+1} \varepsilon_\mathrm{i}^2 + \sqrt{5} \sum_{60-L_{min}+2}^{n} \varepsilon_\mathrm{i}^2 \qquad (3)$$

However, it should be noted that for the hall “D,” different weightings of $\sqrt{500}$ and $\sqrt{50}$ were used for low and high levels, respectively. This is mainly because the music in the smallest hall “D” is louder and dominant over the whole measurement time, thus this hall requires a high weighting for the low levels and consequently another high weighting for the high levels to counterbalance.

Figure 2 shows two fitting results, one using RSS in Eqn. (2) and the other using the weighted RSS in Eqn. (3), indicating an improvement of the fitted model using the weighted RSS.

2.4 Extraction of the audience noise

After a successful fitting process, three Gaussian distributions were identified. The Gaussian distribution curve with the lowest mean level is associated with the mixed background noise, consisting of the technical background noise and audience noise. To determine if the audience noise is extractable, L_{90} of the mixed noise is compared with the mean of the technical background noise distribution (μ_{BN}). If L_{90} of the mixed noise is equal or higher than μ_{BN}, it is an indication that the audience noise is not negligible as compared with the technical background noise.

First, for the two Gaussian distribution curves of the mixed and the technical background noise, two sets of 500 000 random samples are generated, similar to a Monte Carlo simulation. The random samples correspond to the sound pressure levels of the two types of noise. Then the levels of the audience generated noise are obtained by energetic subtraction of the sound pressure levels for technical background noise from the mixed background noise. Using the subtracted levels, a Gaussian distribution of the audience noise is obtained.

2.5 Single number rating of the audience noise

Audience noise is not steady in most cases, since it includes many transient sounds such as a cough, snort, sneeze, clothing rustling sound, paper program rustling noise, and whispering among the audience, etc. What is interesting is the background noise of the audience noise throughout the performance. The single-valued descriptor of the audience noise is chosen to be L_{90} of the audience noise distribution. If L_{90} of the audience noise (named “audience noise level” and designated as L_{AN}) is higher than L_{eq} of the technical background noise, which is nearly steady, then it is obvious that the audience noise during the performance is dominant over the technical background noise.

2.6 Empirical models

Empirical prediction models were developed based on the diffuse field theory. A number of noise sources are assumed to be well distributed over the concert halls, and have the same sound power, which will lead to a constant audience noise all over the performance spaces. Therefore the audience noise level is supposed to be a linear function of the log(N) and log(A), where N is the number of audience and A is the equivalent absorption area.

Once the models are developed, the goodness of the regression models are evaluated using an adjusted coefficient of determination R_a^2.

3 RESULTS

For the investigated halls, the measured reverberation times are listed in Table II, which are fairly similar for the four concert halls, while those for the opera house are shorter. Table III lists the audience noise levels, technical background noise levels, and the means of the dominant Gaussian distributions.

Figure 3 shows the mean values and 95% confidence intervals of the technical background noise levels and audience noise levels for the five halls:

Concert Hall "A": The audience noise is found at frequencies from 500 Hz to 4 kHz. Figure 3(a) shows the technical background noise, and the audience noise level of the hall "A." The audience noise level overlaps with the technical background noise in the 1 kHz octave band, which means they are not statistically different. The mean level difference between the audience noise level and the technical noise level is around 5 dB.

Concert Hall "B": The audience noise level is found only in the two octave bands of 2 kHz and 4 kHz, where the technical background noise levels are fairly low, as can be seen in Fig. 3(b).

Concert Hall "C": The extracted audience noise levels in the three octave bands from 1 kHz to 4 kHz are statistically different from the technical background noise, while the audience noise level in the 500 Hz band is not, as can be seen in Fig. 3(c). The mean difference between the audience noise level and the technical background noise around 10 dB.

Concert Hall "D": The extracted audience noise level from 1 kHz to 4 kHz is statistically different from the technical background noise, as can be seen in Fig. 3(d). The mean level difference between the audience noise level and the technical background noise around 9 dB, similar to the hall "C."

Opera house "E": Because the hall is extremely quiet at high frequencies, the technical noise cannot be evaluated above 4 kHz. It is noteworthy to mention that opera performances are likely to be rather noisy, since there is much stage equipment moved around during the performances and such noises could be included in the mixed background noise, possibly resulting in an overestimated audience noise level. The audience noise levels are extracted over the frequency range from 125 Hz to 8 kHz, showing 13 dB larger than the technical noise level on average.

4 ANALYSIS AND DISCUSSION

4.1 Correlation analysis

Note that only the first four concert halls are included in the following analysis, since the hall "E" is another type of performance space, being an opera house. The audience noise level is likely to be dependent on the following factors: (1) the technical background noise level (L_{BN}), (2) the mean value of the most dominant Gaussian distribution, which is most likely the orchestra sound (L_{DG} or μ_{MUSIC}), (3) the equivalent absorption area (A), (4) the size of audience (N). Under the assumption of a diffuse field, logarithms of the third and fourth explanatory variables were used in empirical prediction models.

A correlation analysis in Table IV showed that the audience noise level is clearly correlated with the background noise, which supports Newton and James's conclusion[3] that the audience reduces their own sound power output during the quiet passages of music in accordance with the quietness of the hall. No other parameters are significantly correlated with the audience noise level. Unfortunately, the variation in log(N) is quite negligible, from 2.8 to 3.1, which is not large enough to affect the audience noise level, although it is believed that the selected performance spaces are good representations of the halls for classical music. In addition, the logarithms of the equivalent absorption area and the size of audience (log(A) and log(N)) are coincidently highly correlated for the investigated halls, having the correlation coefficient of 0.87 between them. This is certainly problematic, since the audience noise level is expected to be proportional to log(N), but inversely proportional to log(A) based on the diffuse field theory.

4.2 Empirical prediction model

Empirical prediction models were developed using the multivariate linear regression analysis. Clearly the technical background noise is the first candidate because of its high correlation. Since there are only four concert halls, the reliability of the prediction models is relatively low.

The simplest regression model using the individual octave band data is

$$L_{\mathrm{AN}} = 7.9 + L_{\mathrm{BN}}, \text{ with } R_a^2 \text{ of } 0.63 \tag{4}$$

and the final statistical model for predicting the audience noise is

$$L_{\mathrm{AN}} = 28.8 + 0.88\, L_{\mathrm{BN}} - 6.6 \log(A), \text{ with } R_a^2 \text{ of } 0.72 \tag{5}$$

4.3 Discussion

The method used in this study is a modification of the method by Hodgson et al.[2] It uses the entire recording to obtain the probability distribution of the short time sound pressure levels in each frequency band, and minimize the error function to find the best fit of the three Gaussian distributions. The method used in this study modified Hodgson et al.'s method[2] in three aspects: the weighted error function, extraction of the audience noise from the mixed background noise, and L_{90} of the audience noise.

Regarding the weighting values in the error function, they vary mainly with the relative proportion of the Gaussian distribution with the lowest level as compared with the other two. However, it is at least systematic, e.g., high weightings are needed when the lowest-level Gaussian distribution curve has a small proportion of time.

The opera house "E" has an unexpectedly high audience noise level when considering its extremely low background noise. Because operas incorporate many elements of spoken theatre, such as acting, scenery, and sometimes dance, the performances are rather noisier than classical orchestra performances. One can come up with two reasons for the high audience noise level: First, the mixed background noise by the fitting method perhaps includes other activity noise such as acting and changing scenery, making it far louder than the technical background noise measured in an empty condition. Second, the audience probably makes more noise, expecting their noise could be masked by other types of the activity noise. Moreover, the recorded performance was more than four hours long which could explain a noisier behavior of the audience.

The audience noise is certainly audible and higher than the technical background noise at mid to high frequencies, which concurs with Kleiner's conclusion.[4] However, the audience generated noise is significantly affected by the technical background noise, which also concurs with Newton and James.[3] In our finding, the audience noise is about 8 dB higher than the technical background noise, according to Eqn. (4). In this regard, it is difficult to strongly argue that the current noise requirements are too strict, since the technical background noise level affects the audience noise. But a compromise can perhaps be found after another thorough investigation in the future.

4.4 Conclusions

In this study, a method for measuring audience noise was suggested and applied in five Scandinavian halls. For full occupancy, the audience noise can be obtained by a fitting of the probability density distributions of the recordings based on three Gaussian distributions. The audience noise level, which is L_{90} of the audience noise distribution, is generally higher than the mean value of the technical background noise, typically in a frequency range from 500 to 4000 Hz. In large concert halls where the background noise is fairly low, the audience noise level is low and not significantly different from the technical background noise, whereas the audience noise levels in smaller halls are clearly noticeable. A correlation analysis showed that the audience noise level is strongly correlated with the technical background noise, and empirical regression models were made accordingly. Because of the strong influence of the technical background noise on the audience noise, a relaxation of the current background noise recommendations is not recommend, but another investigation might be needed to find a compromise.

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Table I – Information about the investigated halls.

Investigated halls	N (persons)	V (m3)	NCB rating
Hall “A” Malmoe concert hall	1198	13500	11 (N)
Hall ”B” Odense Carl Nielsen hall	1272	14000	13 (N)
Hall ”C” Soenderborg Alsion hall	823	9800	15 (H)
Hall ”D” Copenhagen Queen’s hall	408	4500	11 (H)
Opera “E” Copenhagen Opera house	1500	11500	10 (N)

Table II – Measured reverberation times T_{20}.

f_c (Hz)	500	1000	2000	4000
Hall “A”	2.00	1.90	1.75	1.34
Hall ”B”	2.11	2.07	1.91	1.56
Hall ”C”	1.95	1.90	1.86	1.56
Hall ”D”	1.98	1.91	1.67	1.06
Opera “E”	1.43	1.35	1.28	1.17

Table III – Audience noise levels, technical background noise levels, and the mean levels of the dominant Gaussian distributions.

		250	500	1000	2000	4000	8000
Hall “A”	L_{AN}	-	19.9	15.7	15.2	14.1	-
	L_{BN}	24.9	15.2	10.1	10.5	7.6	-
	L_{DG}	67.2	67.8	63.5	59.1	48.1	36.6
Hall “B”	L_{AN}	-	-	-	21.7	15.0	-
	L_{BN}	22.3	20.1	12.6	11.3	8.2	-
	L_{DG}	68.9	70.5	64.2	60.8	51.8	34.8
Hall “C”	L_{AN}	-	26.4	26.5	26.4	19.7	14.3
	L_{BN}	25.8	22.0	16.2	12.9	10.5	9.5
	L_{DG}	61.6	67.4	62.9	54.2	46.0	29.9
Hall “D”	L_{AN}	26.9	22.5	20.1	18.2	18.3	-
	L_{BN}	16.4	13.0	10.1	9.3	11.0	13.8
	L_{DG}	68.6	72.4	69.9	62.5	55.5	31.4
Opera “E”	L_{AN}	28.2	27.3	26.2	24.7	19.8	-
	L_{BN}	20.3	17.0	13.3	8.1	-	-
	L_{DG}	61.8	69.1	62.2	58.6	54.4	32.2

Table IV – Correlation matrix for the explanatory parameters using individual data in the octave bands from 500 Hz to 4 kHz. Only correlations with p-values lower than 0.05 are listed and correlations with p-values lower than 0.001 are marked as bold.

	L_{AN}	L_{BN}	L_{DG}	log(A)	log(N)
L_{AN}	**-**	**0.81**	0.53	-0.54	**-**
L_{BN}		**-**	0. 51	**-**	**-**
L_{DG}			**-**	-0.71	**-**
log(A)				**-**	**0.87**
log(N)					**-**

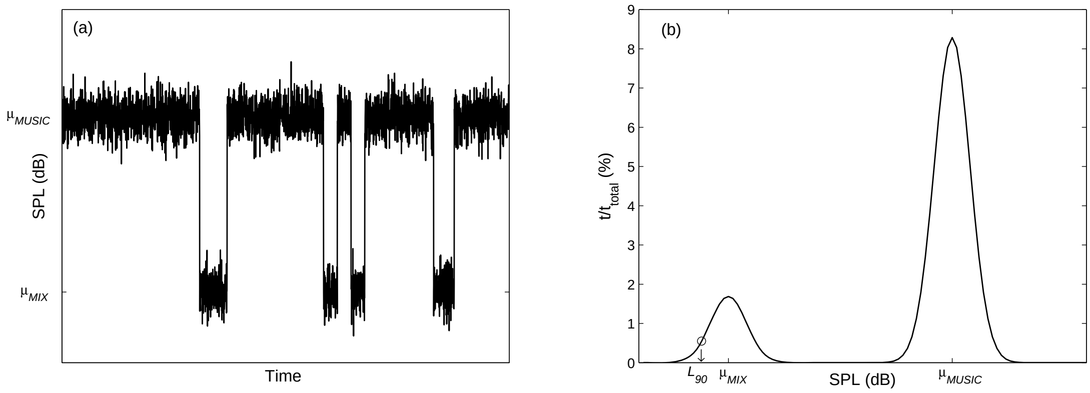

Fig. 1 – (a) An imaginary time history, (b) a probability distribution of the sound pressure level. The high level corresponds to the primary signal (music or speech), and the low level corresponds to the mixed background noise.

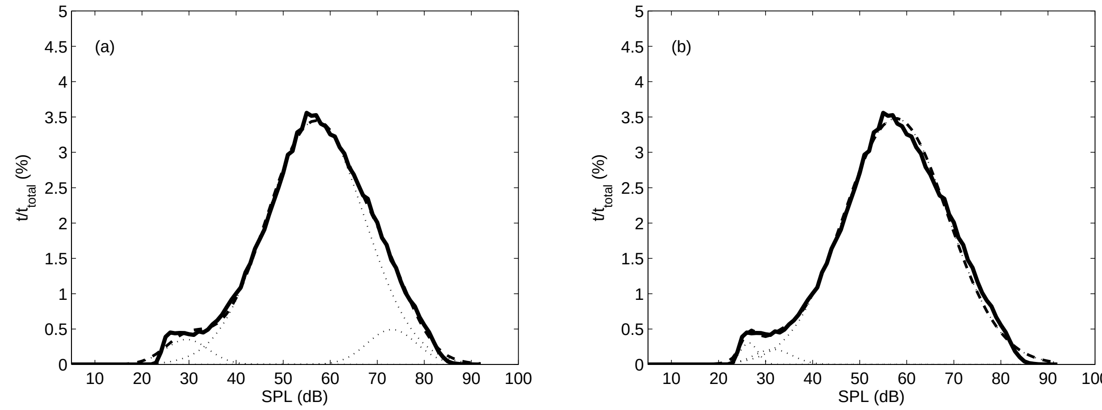

Fig. 2 – Regression of the probability density function. : *Measured probability density function (p_e),* - - - - - -*: individual Gaussian distributions.* — — — *: regressed probability density function (p_m) summing the three Gaussian distributions. (a) Using RSS in Eqn.(2), (b) using RSS_w in Eqn.(3).*

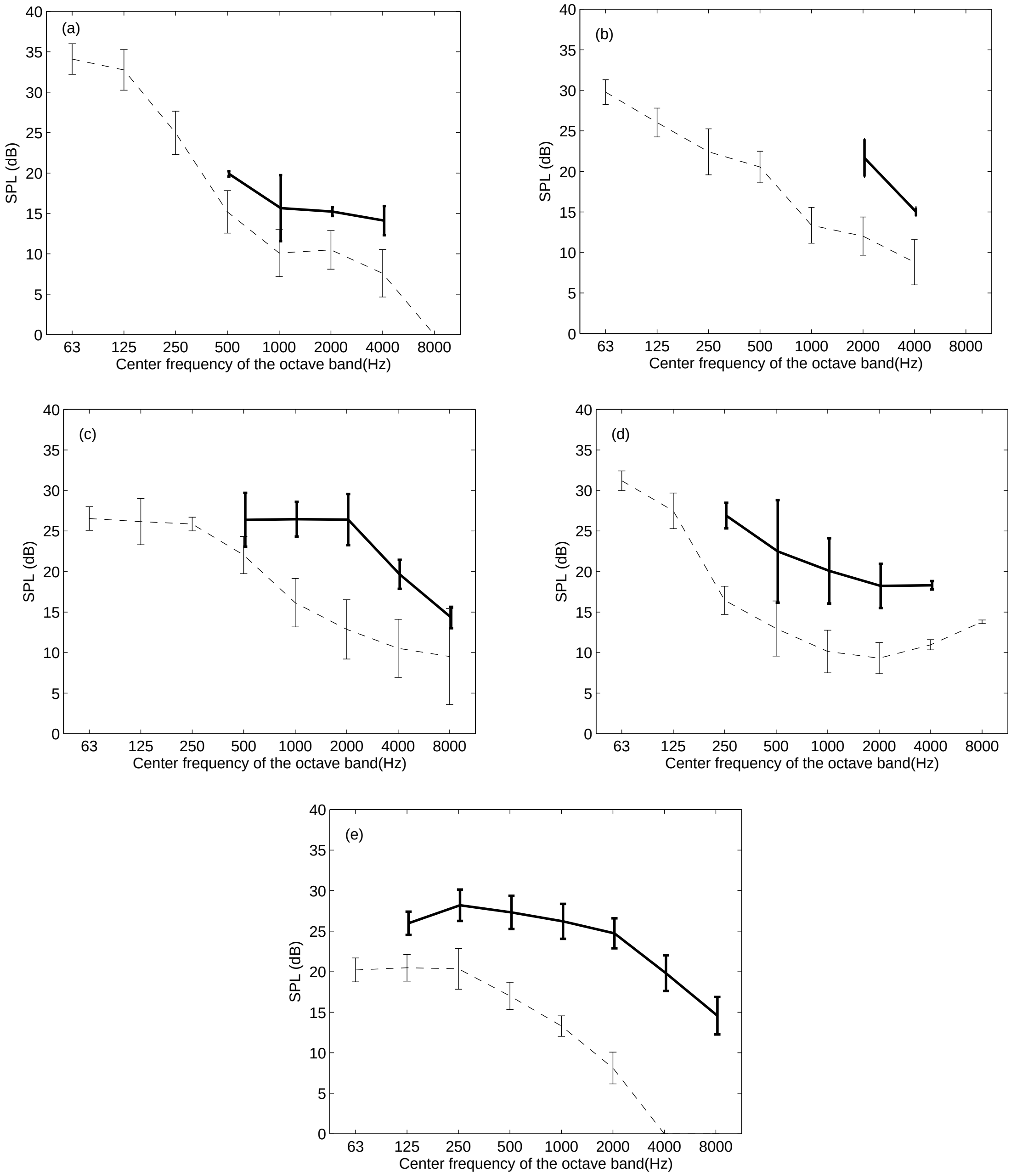

Fig. 3 – Mean values and their 95% confidence intervals of the technical background noise level and the audience noise level in octave bands. : audience noise level, : technical background noise level. (a) Hall "A", (b) hall "B", (c) hall "C", (d) hall "D", (e) opera "E".