

# Sound pressure level limits for stage machinery noise in operas and theaters

Anton Melnikov<sup>a,b,\*</sup>, Ingo Witew<sup>c</sup>, Marcus Maeder<sup>a</sup>, Monika Gatt<sup>a</sup>, Michael Scheffler<sup>d</sup>, Steffen Marburg<sup>a</sup>

<sup>a</sup> Vibroacoustics of Vehicles and Machines, Technical University of Munich, Garching 85748, Germany

<sup>b</sup> SBS Bühnentechnik GmbH, Dresden, Saxony 01259, Germany

<sup>c</sup> Institute of Technical Acoustics, RWTH Aachen University, Aachen 52074, Germany

<sup>d</sup> Applied Mechanics Group, University of Applied Sciences, Zwickau 08056, Germany

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## ABSTRACT

The absence of disturbing background noise is a fundamental minimum requirement for performances in opera houses and theaters. Although the acoustic design of such venues has reached some maturity and specifications for maximum allowable background levels can be found in almost every other textbook on auditorium design, it can be observed that tender documents show a noteworthy variance in published requirements. Oftentimes, the levels that need to be achieved fall significantly below commonly quoted reference values. In order to keep the specifications at a reasonable level and to reduce costs for the (public) developer and builder it seems reasonable to review long-serving guidelines and determine if they suffice for today's performance practice.

This work presents limits for the stage machinery based on measurements conducted during live performances at four well-known performance art spaces in Germany. To ensure inaudibility of the stage machinery, the limits refer to the quietest performance moments without stage machinery noise, music, speech, or other noise events. Based on these limits the stage machinery developer receives a guideline, which helps to design high-quality machinery in terms of noise. Furthermore, these limits help to refine the noise requirements for stage machinery in tender documents.

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## 1. Introduction

Administrations of opera houses and theaters strive to impress their audiences with great performances using lights, sounds, drama, and much more. To be able to enjoy the performance, the attendees should be exposed as little as possible to disturbances like blocked sight lines, uncomfortable chairs, blinding light, or noise. Depending on the origin of the disturbance, finding a solution to fix the problem can be challenging at times. Especially the noise produced by the machines or spotlights can be very annoying and difficult to resolve.

Occasionally, the only possible solutions are replacing the disturbing equipment with quieter products or avoiding the scenic use of noisy hardware in the first place. This may not always be possible, especially for bigger machines like turntable stages, stage wagons and stage elevators [1,2], especially if those are essential for providing important scenic movements. For this reason, noise should be considered in the design process of stage equipment.

Such a development process presupposes appropriate noise requirements.

In the following, different existing requirements and standards for noise in auditoria are discussed, especially concerning applicability to stage machinery. Also the available sources to machinery noise, particularly stage elevators, are analyzed. This is done to answer the question:

- Which noise limits should be applied to stage machinery?

### 1.1. Noise in auditoria

The requirements for technical background noise in auditoria are commonly mapped by the Noise Criterion (NC) [3,4], Preferred Noise Criterion (PNC) [5], Noise Rating (NR) [6], Balanced Noise Criterion (NCB) [7,8], or Room Criterion (RC) curves [9]. For opera houses and drama theaters similar limits of NC20 have been recommended by Beranek [3], Barron [10], or Gade/Rossing (ed.) [11], but sometimes NC15 or PNC15 is used separately for continuous building services noise. This corresponds to a sound level of about 20 dB(A). These limits are primarily aimed at steady-state technical noise, but not at non-steady-state stage machinery noise.

\* Corresponding author at: Vibroacoustics of Vehicles and Machines, Technical University of Munich, Garching 85748, Germany.

E-mail address: [anton.melnikov@tum.de](mailto:anton.melnikov@tum.de) (A. Melnikov).

Stage machinery usually provides very short operating durations and interacts with the audience noise. Therefore, the audience noise has to be considered for stage machinery noise requirements.

One of the first mentions of the audience noise levels in live concert halls reveals a minimum level of 33 dB(A) [12]. Later measurements e.g. in Sýnderborg Alslion hall similarly indicate 32 dB (A) ( $L_{90}$  of audience noise distribution, sum over octaves [13]), however Malmý concert hall, Odense Carl Nielsen hall, and Copenhagen Queen's hall show lower levels [13,14]. Moreover, this study points out the correlation between audience noise and background noise [13]. Though concert halls are regularly equipped with stage machinery, in the vast majority its scenic use during the performance is neither intended nor possible. This is different in operas and theaters, where the machinery movement can be part of the performance.

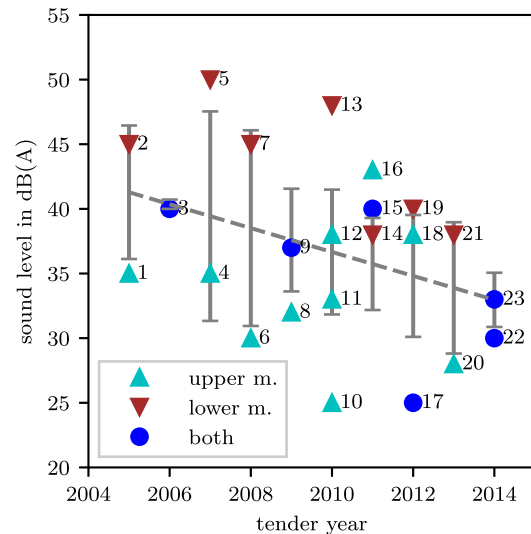
Unfortunately, data of audience noise measured in opera houses or theaters is sparse. One of the few investigations besides that in Copenhagen Opera house [13,14] was conducted in the Gothenburg Town Theater [15]. During a series of theatrical live performances with 600 visitors on average a level of 35.5 dB(A) was measured. To provide better insights, it makes sense to collect additional measurement data with broader spectral range and more performance art spaces included.

### 1.2. Stage machinery noise

In case of stage machinery, noise optimization is motivated by levels that are imposed by tender documents or literature. The limits required by a wide selection of tenders between 2005 and 2014 shown in Fig. 1 give an overview of the current market situation. The data contains requirements (triangles and circles) between 25 dB(A) and 50 dB(A), measured in the first row of auditoria. The linear regression over time (dashed gray line) shows a decreasing trend. Such a trend demonstrates an increased demand for quiet stage machinery. It seems therefore reasonable to expect strict noise limits such as < 35 dB(A) rather than lenient limits (see Fig. 1, points 5 and 13) in future tenders. The presented data shows a large range of levels and cannot be used to derive a general limit. This constrains the limit derivation to the available literature.

The requirements valid specially for stage machinery noise in theaters and operas are not represented in the international literature. Nevertheless, to get an overview national literature can be used. One of the few available publications proposes the following limits: drama theater, 35 dB(A) for lower machinery and 45 dB(A) for upper machinery; musical theater, 40 dB(A) for lower machinery and 45 dB(A) for upper machinery [17]. Comparing the outcomes of this study with the tender documents in Fig. 1 shows that 34% of the tenders underestimate the proposed limits, only 9% match it exactly and a majority of 57% overestimate it. Even though 9% of the shown tender values match the proposed level in the literature exactly, there is no general consensus between tender and literature.

The limits from tenders and literature feature an additional aspect requiring clarification, namely its technical feasibility. In an experiment Schirmer and Ulrich [18,19] compared the levels generated by 8 different power train systems of stage elevators moving at 0.3 m/s, measured in the first row of auditoria. Their recorded levels range from 35 dB(A) for an electric motor with ropes to 71 dB(A) for an electric motor with screw jack. Values in between cover 37 dB(A) and 40 dB(A) for two systems with hydraulic motor and ropes, 40 dB(A) for two systems with hydraulic cylinder and ropes, and 40 dB(A) and 47 dB(A) for two systems with electric motor and gear racks. In light of the understage machinery limits proposed by Tennhardt [17], there is only one power train that barely accomplishes the published drama theater limit of 35 dB(A). Half of the tested systems meet the suggested



**Fig. 1.** Sound level requirements at first auditorium row from tender documents between 2005 and 2014 [16], separated by limits for upper machinery (light-blue triangles), lower machinery (flipped brown triangles) and one limit for both machinery types (blue circles). Gray dashed regression line shows a decreasing trend. Error bars illustrate the standard deviation with respect to the regression line. 2005: Großes Haus Gera (1) upper and (2) lower machinery (unspecified); 2006: (3) National Opera and Ballet of Belarus (unspecified); 2007: House of Musical Arts Muscat (4) upper and (5) lower machinery (unspecified); 2008: Mariinsky Theater St. Petersburg (6) upper and (7) lower machinery (unspecified); 2009: (8) Das Meininger Theater upper machinery ( $L_{Aeq}$ ), (9) Kammerspiele Paderborn (unspecified); 2010: (10) Classical Theatre of Opera and Ballet Astana upper machinery ( $L_{Aeq}$ ), (11) Schauspiel Frankfurt upper machinery ( $L_{Aeq}$ ), Musiktheater Linz (12) upper and (13) lower machinery (unspecified); 2011: (14) Berlin State Opera lower machinery (unspecified); (15) Yanka Kupala National Academic Theatre Minsk (unspecified); (16) Berlin State Opera upper machinery (unspecified); 2012: (17) Grande Auditorio Gulbekian (unspecified); Artpalace 'Neftjanik' Surgut (18) upper and (19) lower machinery (unspecified); 2013: Saarländisches Staatstheater (20) upper and (21) lower machinery (unspecified); 2014: (22) Deutsche Oper Berlin ( $L_{Aeq}$ ), (23) Bühnen der Stadt Köln ( $L_{Aeq}$ ).

musical theater limit of 40 dB(A). It should be mentioned that the informative value of measurements from 2002 may have changed due to improved gear and electric motor technology. At present, appropriate boundary conditions inside the building and sufficient design effort can lead to extraordinarily quiet stage elevator installations, such as in Operaen Copenhagen with 27 dB (A)–30 dB(A) during one operation cycle [20]. However, there is no further evidence known in literature for the technical feasibility of stage elevators generating noise levels under 30 dB(A) during a whole operation cycle.

Finally, the topic of stage machinery noise needs to be discussed from an economic and artistic point of view. It must be clear to all involved parties that a continuous reduction in the permissible noise levels (in tender documents) leads to a (presumably exponential) increase in costs for the customer. It is certainly difficult or impossible to determine the price of artistic freedom, but nevertheless it is desirable to have a perspective that can be quantified. In terms of machinery noise limits, this can be achieved by collecting data that shows how often a given SPL occurs during a performance without machinery noise. Setting the limits for machinery noise at an appropriately low SPL will ensure that the any machinery noise will be masked by naturally occurring background noise.

All this stresses the need for more detailed data, which can be obtained only by conducting new measurements. Measurements of the noise during a performance can reveal an answer to the refined research objective:

- Which spectral noise limits should be applied to stage machinery in operas and theaters?

This study reports on acoustic measurements during live performances in 4 venues (opera houses and theater). The collected data extends previous knowledge of the spectral composition and the likelihood of occurrence of a given Sound Pressure Level (SPL) during opera, ballet and theatrical performances. Different evaluation methods are discussed which allow a differentiated approach to limits for background noise that goes beyond single-value parameters currently available in the literature. The determined background noise limits for stage machinery are independent of the particular stage machinery at the venues that were part of this study, since the stage machinery was inactive during the periods that were investigated. The discussion addresses aspects that are unique to noise from stage machinery that is transient in nature and consists of short term events.

## 2. Method

### 2.1. Measurements

With the goal to collect performance noise data including spectral content acoustical measurements were conducted under realistic conditions and under normal operation. The noise was measured directly during live performances from the receiver perspective. The measurement position was in the middle of the first row of audience seating [21]. This is a typical measurement position used for quality acceptance tests during the handover phase of newly built or renovated performance art spaces. This is in line with current tender documents [21] and previous investigations [17–20] discussing stage machinery noise. Compared to other possible listener positions this is the most critical one due to the shortest distance to the noise source. The placement of the microphone was 120 cm above the floor according to ISO 3382-1 [22].

To cover the complete audible frequency range, the SPL was measured over the frequency range from 12.5 Hz to 20 kHz. To capture low SPL accurately a microphone with an intrinsic noise of less than 20 dB was chosen. To be able to catch the short breaks during the music or actor speech, the data was recorded in 100 ms intervals.

#### 2.1.1. Equipment

The handheld analyzer type 2270 from Bruel&Kjaer was used for measurements. The specifications for the 1/2-inch free-field microphone type 4189 with ZC-0032 preamplifier are given in the Bruel&Kjaer product manuals [23,24]. The microphone was calibrated with the Bruel&Kjaer pistonphone type 4228 before and after every measurement.

#### 2.1.2. Measurement venues

The measurements were conducted during 12 performances at 4 different venues. In the case of day-to-day business of the venues it is challenging to get permission to measure live opera performances at the required measurement position. This leads to significant limitations concerning sample size. In this study, the sample size is comparable to well-known studies on audience noise [15,13,14,25].

The venues were selected to obtain a variety in program at a quality standard that is 'setting the tone' on an international scale [26] and are shown in Table 1. Since opera is the performance type, where it is more common to expect occasional stage machinery operation, the choice of venues and pieces is focused on it. Additionally, a drama theater was included, which is a middle-sized typical theater house that reflects the wide-spread state of technology and artistic performance practice.

In addition to the performance measurements, stationary background noise measurements were conducted at the surveyed

**Table 1**

Places for measurements including the type, the year of last significant renovation or refurbishment, and the number of seats.

Venue	Type	Renovation	Seats
(a) Semperoper Dresden	Opera	1985	1270
(b) Leipzig Opera	Opera	2007	1267
(c) Bayerische Staatsoper	Opera	1963	2101
(d) State Playhouse Dresden	Theater	1990	785

venues. These were done over at least 60 s for each venue during full operation of potential noise sources such as Ventilation and Air Conditioning (HVAC). All included venues fulfill NC20 and PNC20, which is appropriate for opera houses and drama theaters [3,10,11]. The spectrum of the background noise (solid blue line) is illustrated in Fig. 4a for venue (a), Fig. 4d for (b), Fig. 4e for (c), and Fig. 9a for (d). Furthermore, the reverberation times in venues (a), (b), and (d) were determined and are shown in Table 2. During this measurement, the receiver position was in the middle of the first row 120 cm above the floor. The position of the impulse source was on the right side in front of the stage, approx. 160 cm above the floor and approx. 10 m away from the receiver position. For venue (c), Table 2 shows the reverberation times available in the literature [28,27]. The reverberation time characterizes the diffuse field, which has an impact on the measured SPL in a hall. Since the considerations are focused on operas and theaters, it is necessary to consider venues with appropriate reverberation time. Venues (b) with 1.4 s, (c) with 1.7 s, and (d) with 1.3 s at 1 kHz lie in the typical range for operas and theater houses [10]. Venue (a) demonstrates a relatively long reverberation time (2 s at 1 kHz), which is confirmed by the data published in literature [26]. According to Barron [10], such long reverberation time design is a current trend in new European opera houses. According to this fact, the venue choice represents state of the art in terms of background noise and reverberation time.

To cover the typical range of genres, 12 different performances were chosen for the measurement. The pieces selected at Semperoper Dresden were 3 operas and 2 ballets. Different epochs were included in the chosen operas, namely *Doktor Faust* (1925) by F. Busoni, *La clemenza di Tito* (1791) by W. A. Mozart, and *Les Contes d'Hoffmann* (1881) by J. Offenbach. The chosen ballets were both from the same epoch but from different genres. *Manon* (1974) is a classical ballet by K. MacMillan and J. Massenet and *Forgotten Land* (1981) is a modern ballet by G. Balanchine, J. Kilián, and W. Forsythe. At Leipzig Opera an opera and a ballet piece were selected: *Die Frau ohne Schatten* (*The Woman without a Shadow*) (1919) by R. Strauss and a neoclassical ballet *Don Juan* (1998) by T. Malandain. It was possible to measure one piece at Bayerische Staatsoper twice: *Un Ballo in Maschera* (1857) by G. Verdi. This allows assessing the consistency of the findings. The repeated measurements were done under reproducibility conditions [B.2.16] [JCGM 100:2008] with the changed condition of 'time' and 'condition of use' as the two performances were recorded on two

**Table 2**

Reverberation times measured in venues (a), (b), and (d) (see Table 1) in octaves. Determined in the middle of the first row in the unoccupied condition and with iron curtain closed. Reverberation times of venue (c) were taken from literature [27,28].

Octave Hz	(a) s	(b) s	(c) s	(d) s
250	-	1.74	1.7	1.59
500	2.02	1.50	1.7	1.45
1 k	1.95	1.42	1.7	1.33
2 k	1.85	1.29	1.6	1.27
4 k	1.52	1.06	1.2	1.17
8 k	1.13	0.77	-	0.88

different days with the entire equipment set up and dismantled for the two measurements. The relatively new piece *Alice's Adventures in Wonderland* (2011) by C. Wheeldon, J. Talbot, and N. Wright was selected as the ballet performance in that auditorium. The pieces measured in State Playhouse Dresden were *Jeder stirbt für sich allein* (*Alone in Berlin*) by H. Fallada and E. Petschinka and *Amphitryon* by H. von Kleist. Through the wide range of pieces covering different cultural epochs in style, it is ensured that the analysis remains valid for a large range of conditions.

## 2.2. Data analysis

For data acquisition and export, the Bruel&Kjaer-Software BZ5503 was used. The A-weighted total equivalent level  $L_{Aeq}$  and the unweighted  $L_{eq}$  in 1/3 octave bands (12.5 Hz–20 kHz) in 100 ms-steps was taken during the entire performance. Here,  $L_{eq}$  is the true equivalent level without time weighting applied. To ensure that only the actual performance time is subject of the analysis, the data was cleaned from applause and intermissions afterwards.

The audience behavior during opera, ballet and theater performance is different from each other (e.g. aria applause in opera). Furthermore, the performance sound pattern is dependent on the performance type, for example short intermissions for entering and leaving dancers typically present in a ballet performance. These differences have a significant influence on the generated noise. To reflect this aspect the data is processed separately for opera, ballet, and drama.

In order to illuminate the collected data from different angles, different data analysis methods are discussed: Minimum 1s-Averaged Level (min1s) level, Gaussian Mixture Model (GMM), and N% exceedance level.

### 2.2.1. Minimum 1 s-Averaged Level (min1s)

The most straightforward way to look for the background noise level over the measurement duration is to use the quietest period of time as was done by Newton & James [25]. An adequate time interval is 1 s, which is based on the subjective duration evaluation of a 1 kHz tone of 60 dB SPL as proposed by Fastl/Zwicker [29, pp. 265–269]. Whereas the data is in 100 ms-steps, the evaluation can make use of this time discretization by moving time average with a rectangular window function of length 1 s in the form

$$L_{min} = \min \left\{ 10 \lg \left( \frac{1}{n} \sum_{i=1}^n 10^{0.1L_{j+i}} \right) \right\}, \quad (1)$$

with  $\min\{\}$  as minimum operator,  $L_{j+i}$  as band filtered or broad band level at sample  $j + i$ , and  $n = 10$  as number of samples in the window. As a result, this procedure yields the min1s level with a better time discretization in 100 ms-steps. A data cut-out is shown in Fig. 2: the black line is the measured total level and the gray region indicates the averaging time.

The charm of a relatively simple parameter is counterbalanced by the potential to overestimate noise requirements. Levels identified using the min1s algorithm occur only once during a performance and are by definition relatively rare. Thus, this metric allows quantifying the moments of dramatic silence, where the audience may collectively hold their breath. Adopting min1s levels as noise requirements for stage machinery may be understood as aiming for the highest possible target, namely ensuring that noise from stage machinery will not be heard during a performance at all. From an engineering point of view additional information that helps interpreting sound levels as they occur during a performance would be desirable. In particular, a SPL likelihood of occurrence during a performance would enable better assessment of the reasonableness of sound levels for limit derivation.

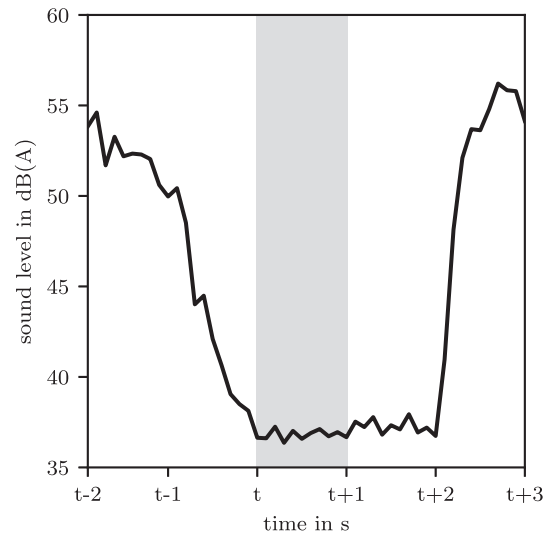


Fig. 2. A-weighted total level of a short break during the performance. Solid black line is the level and the gray region indicates the averaging time for obtaining the min1s level.

### 2.2.2. Gaussian Mixture Model (GMM)

To consider the occurrence probability and to allow more in-depth level analysis a statistical perspective can be useful. GMM [30] is an established method in noise studies. The effectiveness of it was demonstrated in several audience and background noise investigations [13,31]. GMM splits a global Probability Density Function (PDF) into multiple normal distributions. This decomposition can be applied on the SPL distribution during the performance (Fig. 3, gray line), whether in 1/3 octaves or as total level. Afterwards every single normal distribution can be considered separately. This allows to remove unwanted noise sources from the PDF or to focus on noise sources of interest.

The GMM represents a linear combination of normal distributions

$$p(x) = \sum_{k=1}^N w_k \varphi_k(x) \quad (2)$$

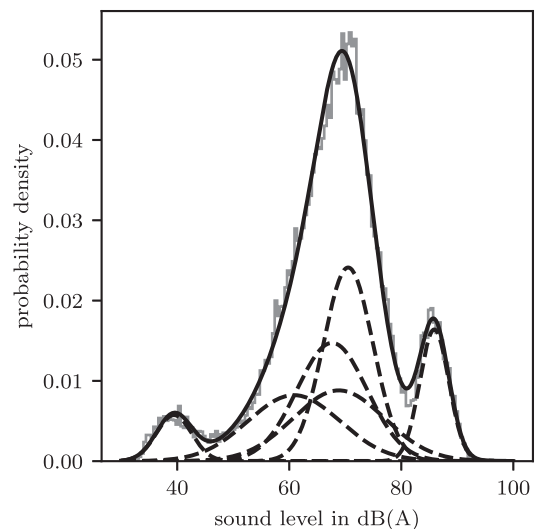


Fig. 3. GMM (solid black line) applied to the measured PDF (solid gray line) of total level in the ballet piece Don Juan. BIC suggests 6 normal distributions (dotted lines) as suitable.

with number of normal distributions  $N$  in the form

$$\varphi_k(x) = \frac{1}{\sqrt{2\pi\sigma_k^2}} e^{-\frac{1}{2}\left(\frac{x-\mu_k}{\sigma_k}\right)^2}. \quad (3)$$

Considering the separated normal distributions, the GMM noise limit is defined by the mean value of the minimum distribution (Fig. 3 left gaussian). This presumes that the background noise is normally distributed and the contribution is sufficient to be detected with GMM. The example histogram in Fig. 3 clearly reveals three peaks. However, a suitable approximation requires a higher distribution number [13,31]. To determine the optimal number Bayesian Information Criterion (BIC) [32,33] is used. Applied on the example in Fig. 3, BIC suggests 6 normal distributions. It is necessary to use an appropriate number of normal distributions to obtain the minimum distribution and subsequently the limit value correctly. In the cases where the smallest cluster of levels is not fitted well enough, there is a danger to underestimate the noise requirements [34].

### 2.2.3. $N\%$ exceedance level ( $L_N$ )

As an alternative to GMM a probabilistic method called  $N\%$  exceedance level ( $L_N$ ) [35,36] can be applied. It directly delivers information about how often a distinct level is exceeded over the measurement time. This type of level-quantile is usually used in traffic noise investigations [37–39] and can also be the basis for more sophisticated models [40,41] or linked with GMM [13].

Based on the intended probability the  $L_N$  noise limit is defined by the exceedance level value. It combines the robustness of the min1s level combined with a probabilistic approach. The benefit of the  $L_N$  method is the known quantile  $N$ , which represents how often the  $L_N$  level is exceeded. Due to the very definition of level-quantile a probability of having fallen below a distinct level limit is automatically obtained. Despite this advantage, for higher occurrence probabilities there is an increasing risk of including performance sounds in the results. This risk can be minimized by adequate choice of the percentile. Accordingly, the percentiles 95 and 99 well represent the important probability range and emerge reasonable for limit derivation.

## 3. Results

### 3.1. Opera

The results for individual opera pieces can be found in Fig. 4. Merged to one data set all opera pieces result in 12.3 h of evaluated opera performance. Data analysis in 1/3 octave bands and in octave bands is shown in Fig. 5. The colored background reveals the cumulative density of the measured data. The black lines denote the  $L_N$  levels, the red line illustrates the min1s level, and the cyan line refers to the mean values from GMM. The background level is represented by the blue line. For individual results the background level is shown for the venue where the piece was measured. For merged results only the maximum value of venues considered in that unique case is illustrated. The quantitative summary of the results is listed in Table 3.

### 3.2. Ballet

The ballet data (5.8 h) is shown in the same way as the data from operas. For individual pieces see Fig. 7 and for the merged ballet data see Fig. 6 and Table 4.

### 3.3. Drama

Figs. 8 and 9 and Table 5 show the same results for theatrical performances based on 4.1 h of recorded material.

## 4. Discussion

### 4.1. Reproducibility of level metrics

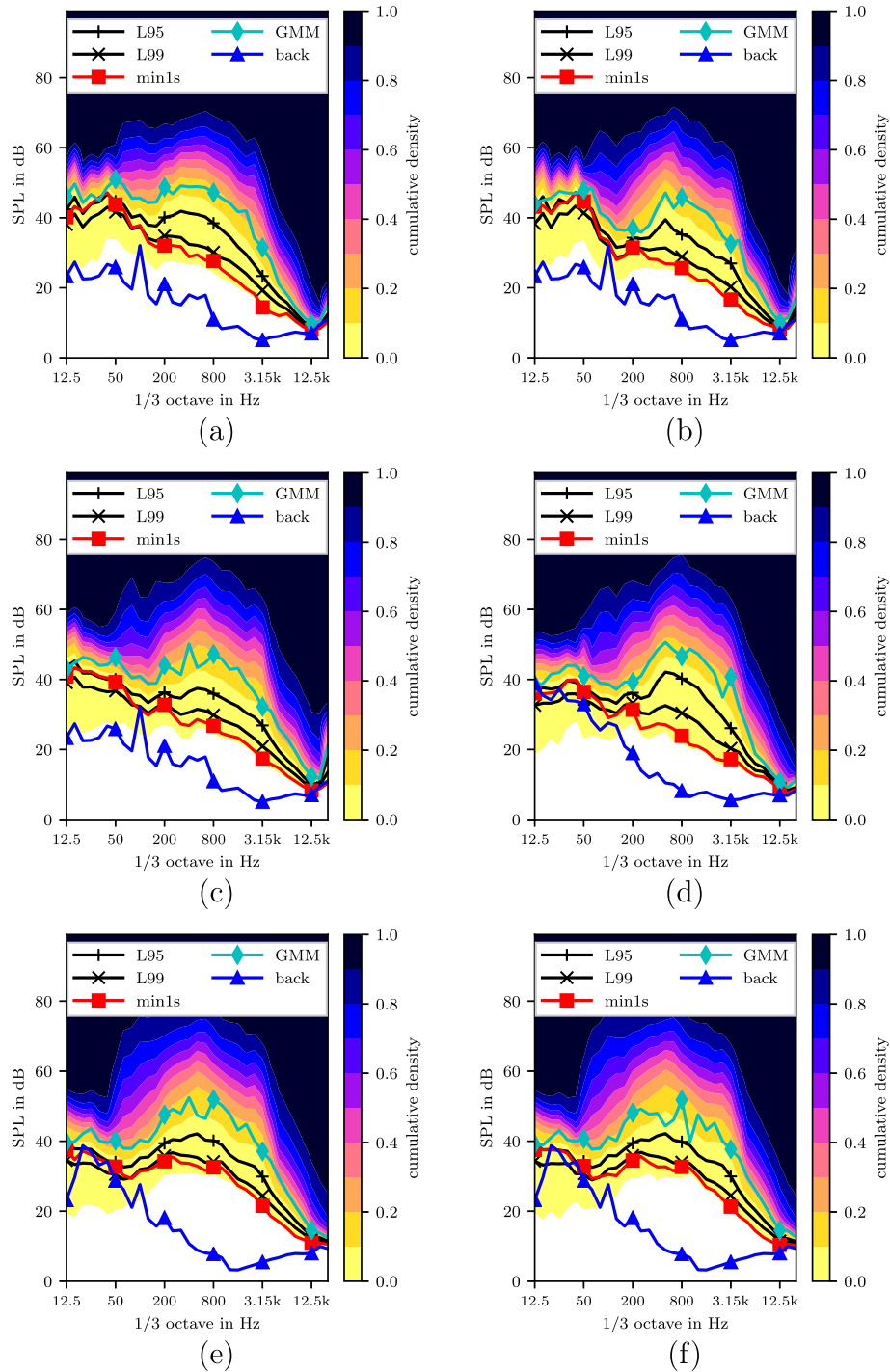
The suitability of the different level metrics can be evaluated based on the reproducibility and on the reasonableness of the results. The reproducibility of the results can be assessed by comparing the two takes of *Un Ballo in Maschera* in Fig. 10. The best reproducibility is achieved by the exceedance levels (see Fig. 10 solid green and magenta lines), where only a small difference with a maximum of 1.4 dB at 31.5 Hz is present.  $L_{\min 1s}$  shows the highest difference of 3 dB at 16 Hz (see Fig. 10 red solid line), which is outside the frequency range important for room acoustics. Above 160 Hz this method shows deviations of less than 1 dB and, hence, may be recognized as a reasonable method to determine SPL limits. The poorest results are generated by the GMM method (see Fig. 10 cyan solid line) with relatively large differences of up to 10 dB at 1 kHz and of 5 dB at 400 Hz.

One possible explanation for this is that in some cases the stationary background noise is not identified by the GMM method as a separate distribution. This situation can arise when the (cumulative) probability of stationary background noise to occur is relatively low and in the same order of magnitude as the fitting residual of the GMM method. With the background noise usually being the distribution with the lowest levels the difference between detecting and not detecting this distribution can be quite significant level-wise. Such problems were not encountered in similar studies [13,31] that also used GMM strategies. This can be traced back to differences in determining the fitting residual. While Jeong et al. [13] used a predetermined number of distributions combined with weighting factors to increase the impact of low level contributions the present study determines the number of synthesizing distributions a posteriori based on the BIC.

### 4.2. Types of performances

All analyzed performance types have in common a global decrease in levels towards higher frequencies. This can be observed in Figs. 5, 6, and 8 for opera, ballet, and drama performances alike. Differences become evident when it is distinguished between performance types and parameter metrics. In drama performances the different level metrics yield very similar results. This is rather evident in Fig. 8b showing an almost strictly monotonic decrease in levels between 16 Hz ( $\approx 50$  dB) and 16 kHz ( $\approx 17$  dB). In contrast, the levels determined during opera or ballet performances are shown in Figs. 5b and 6b. These illustrate a larger spread in levels at mid frequencies for the different metrics. Also, for some parameters the generally decreasing trend is interrupted between 125 Hz and 4 kHz by a local maximum at mid frequencies (e.g. see Fig. 5b, GMM level of 57 dB at 500 Hz for opera performances).

As this increase in level matches the frequency range associated with music (55 Hz–4 kHz [11]), the elevated levels are likely caused by the performance music during the recordings. The exact comparison of the different level metrics in opera and ballet performances shows that the different parameters provide a different resilience against detecting performance sounds. In Figs. 5b and 6b,  $L_{GMM}$  and  $L_{95}$  yield relatively high levels compared to  $L_{\min 1s}$  and  $L_{99}$ . The latter two parameters show relatively similar results for ballet performances over the entire frequency range, but also for opera performances over a wide frequency range.



**Fig. 4.** Opera individual measurements and analysis results. (a) *Dr. Faust*, (b) *Titus*, (c) *Les Contes d'Hoffmann*, (d) *The Woman without a Shadow*, (e) *Un Ballo in Maschera* – take 1, (f) *Un Ballo in Maschera* – take 2.

In the case of opera and ballet results, it is observed that the background noise at frequency bands below 160 Hz is sometimes higher than the min1s and  $L_{99}$  results, see Figs. 5 and 6. Since the background level (blue solid line) is the maximum of all considered venues for each performance type, it can slightly exceed the levels obtained by the noise metrics. Also the individual results can demonstrate such a behavior, see for example Fig. 4e or Fig. 7c. This is mainly attributed to higher likelihood of measuring extreme low level due to much longer measurement time during the performance compared to the relatively short background noise measurement.

#### 4.3. Stage machinery imperceptibility probability

The experimentally determined relationship between SPL and the probability of exceedance  $N$  does not yet provide a direct foundation to predict the likelihood of hearing stage machinery as it is not operated continuously during the entire performance. In fact, stage machinery is audible during a performance precisely when the two events 'SPL falls below  $L_N$ ' and 'stage machinery operates' occur simultaneously. This relationship can be represented mathematically by

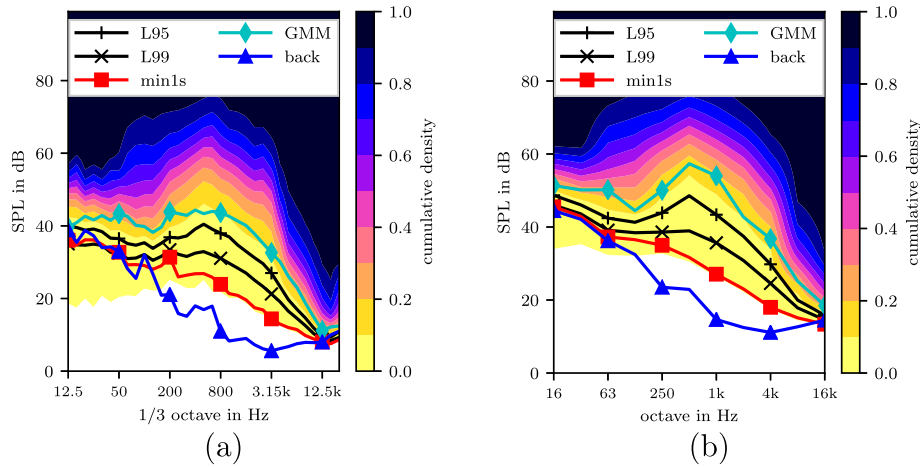


Fig. 5. Opera measurement and analysis results. (a) in 1/3 octave bands, (b) in octave bands.

**Table 3**  
Merged opera results: min1s levels, GMM minimum mean values and  $L_N$  levels.

Octave Hz	min1s dB	GMM dB	$L_{95}$ dB	$L_{99}$ dB
16	45.5	51.4	48.7	46.0
31.5	42.9	50.2	46.1	43.6
63	37.3	50.2	42.4	39.1
125	36.5	44.5	41.3	38.4
250	35.0	49.5	43.9	38.6
500	31.7	57.4	48.6	38.9
1 k	27.1	54.0	43.4	35.7
2 k	23.0	42.8	37.5	30.8
4 k	18.0	36.1	29.8	24.6
8 k	15.1	25.2	20.0	17.8
16 k	13.4	18.5	15.8	14.6
Total (A)	34.8	58.1	52.1	42.9

**Table 4**  
Merged ballet results: min1s levels, GMM minimum mean values and  $L_N$  levels.

Octave Hz	min1s dB	GMM dB	$L_{95}$ dB	$L_{99}$ dB
16	45.1	51.4	49.6	46.7
31.5	45.3	53.4	48.4	45.8
63	40.0	50.1	45.8	42.7
125	35.5	50.7	41.9	38.2
250	32.9	54.6	47.9	38.4
500	31.2	46.8	48.0	36.6
1 k	28.1	42.5	44.0	32.5
2 k	24.9	40.7	38.3	29.1
4 k	18.6	35.5	28.9	22.9
8 k	14.2	23.4	19.6	16.6
16 k	12.8	21.7	16.1	13.7
Total (A)	33.7	48.5	52.2	40.0

$$P_{imp} = 1 - P_{SM} \cdot (1 - N). \tag{4}$$

The imperceptibility probability  $P_{imp}$  during a performance is a function of the percentile of the exceedance level  $N$  and the probability of stage machinery operation  $P_{SM}$ .

Technically, to prevent overheating, the operation of machinery is limited by the intermittent periodic duty S3 to 40% [42]. A probability of  $P_{SM} = 40\%$  may seem to overestimate the actual usage of

stage machinery by far, given wide-spread rules of thumb suggesting a maximum use of five complete up and down cycles during a performance. Based on an average performance duration of 111 min and five 6 m strokes of 0.3 m/s (200 s in total) this leads to an adequate and realistic operation probability of  $P_{SM} \approx 3\%$ . For the arbitrary choice of having stage machinery with noise characteristics that fall below the levels defined by  $N = 99\%$ , Eq. (4) yields an imperceptibility probability of  $P_{imp} \approx 99.97\%$ .

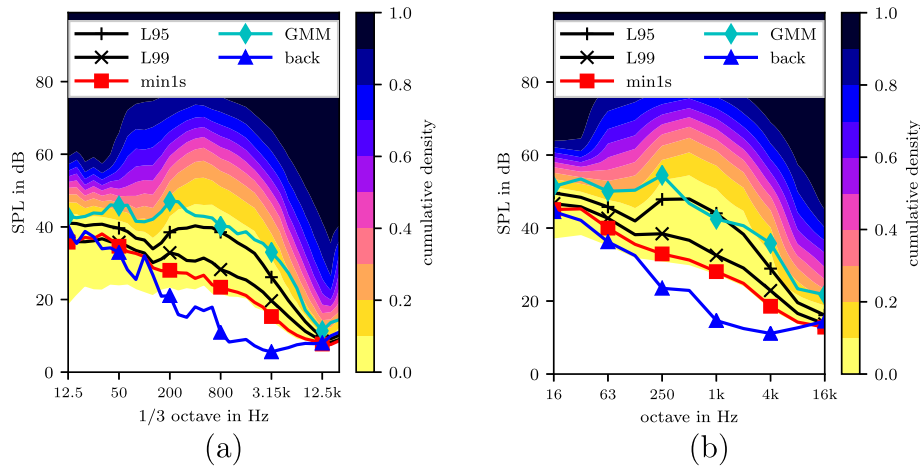


Fig. 6. Ballet measurement and analysis results. (a) in 1/3 octave bands, (b) in octave bands.

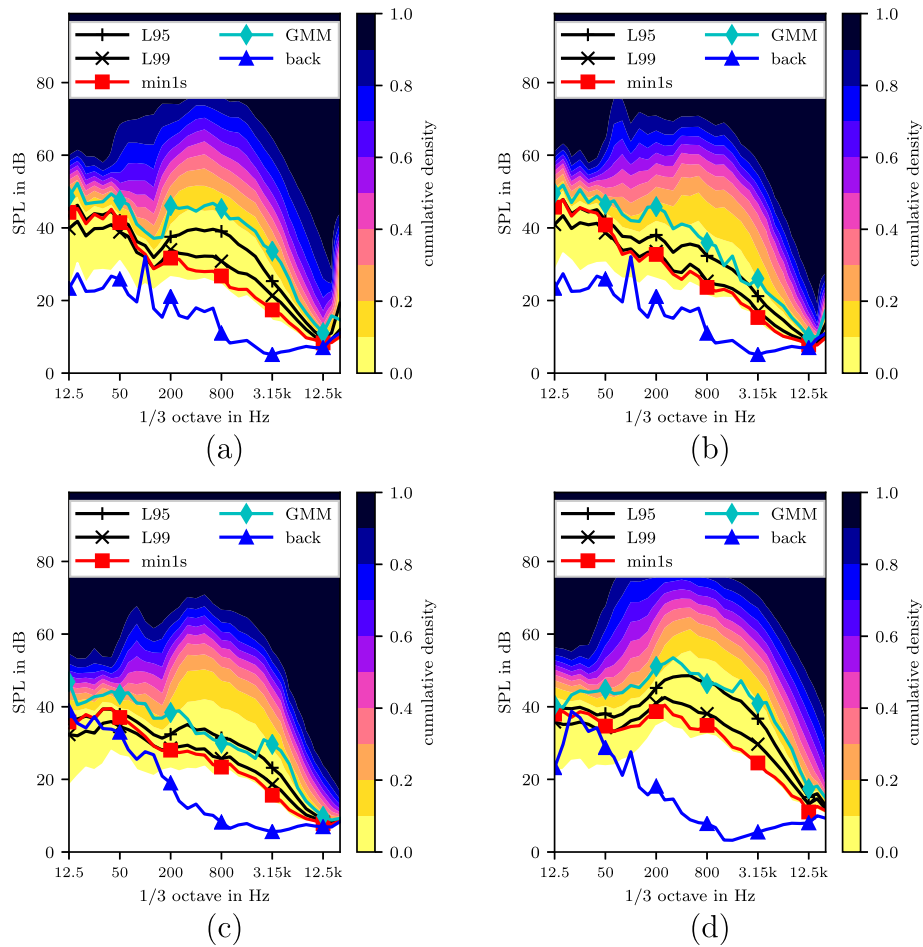


Fig. 7. Ballet individual measurements and analysis results. (a) *Manon*, (b) *Forgotten Land*, (c) *Don Juan*, (d) *Alice's Adventures in Wonderland*.

Obviously this assumes that the events 'SPL falls below  $L_N$ ' and 'stage machinery operates' are uncorrelated to each other. In situations where machinery operation is purposely aimed at silent moments the presented concept is not applicable. The risk of  $L_N$  being influenced by operating stage machinery cannot be excluded beyond the smallest doubt since there is no data available showing the noise characteristics of the moving stage elevators in the otherwise silent halls. As long as the assumption holds that both events discussed earlier are uncorrelated, it can be maintained that the noise of the stage machinery probably does not affect the exceedance levels. The semantic analysis of the min1s events provides some support for the assumption that the stage machinery was not operated in the quietest moments deliberately.

#### 4.4. Spectral content

Compared to the levels of individual performances or different pieces in Figs. 4, 7, and 9 the merged data of all pieces (see Figs. 5, 6, and 8) of the same genre shows a much more homogeneous trend over frequency which is due to the longer measurement time. A similar smoothing effect should be expected when comparing the octave band levels in Figs. 5b, 6b, and 8b to the same levels determined for 1/3 octave bands. On closer inspection, however, a second effect can be seen. The determined levels at an octave band resolution are higher compared to what would have been expected based on simple level addition of contributing 1/3 octave levels. This discrepancy can be attributed to the fact that the level minima in the octave bands do not coincide in time with the minima of the 1/3 octave bands.

In the stage machinery industry it is common to consider noise requirements in single-number values (see Section 1.2), but this approach ignores the spectral composition of the noise. Considering Figs. 5b, 6b, and 8b, the distribution of the performance noise is dependent on frequency. Limit definition without considering this dependency can be a problem especially in the case of narrow-band noise typically generated by machines. The 1/3 octave bands provide best details about the frequency distribution of noise, but the number of values can be inconvenient for practical use. The consideration in octave bands as an established practical approach for noise criteria [3,4,7–9] reduces the data compared to 1/3 octave while still revealing sufficient information. Therefore, octave bands (see Tables 3–5) are best suited to define the noise limits.

The last aspect to discuss regarding spectral content is the suitability of the limits for noise sources with known characteristics, i.e. featuring tonality or impulsive impact noise during operation. The audibility of tonal components in noise spectra depends a lot on spectral masking. As masking can only be discussed in critical bandwidths (i.e. 1/3 octave bands for mid and high frequencies) octave band noise limits are not sufficient. From a practical point of view a limit penalty of up to 5 dB to the octave band limits may seem appropriate. The scientific sustainability of such rules of thumb should be subject to future investigations.

#### 4.5. Comparison to tender documents

The determined total levels can be compared with the total levels published in tender documents. Fig. 11 shows the histogram



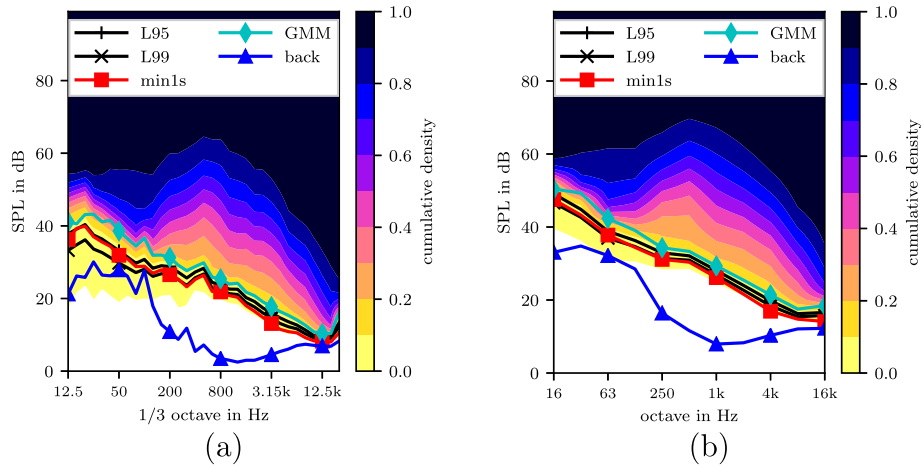


Fig. 8. Drama measurement and analysis results. (a) in 1/3 octave bands, (b) in octave bands.

Table 5  
Merged drama results: min1s levels, GMM minimum mean values and  $L_N$  levels.

1/3 octave Hz	min1s dB	GMM dB	$L_{95}$ dB	$L_{99}$ dB
16	47.5	50.4	49.1	46.6
31.5	43.3	49.3	44.8	42.7
63	37.8	42.3	38.8	37.0
125	34.4	39.0	36.3	34.6
250	31.1	34.3	32.9	31.4
500	30.4	33.3	32.1	30.9
1 k	26.2	29.3	28.1	26.9
2 k	21.6	25.5	24.0	22.7
4 k	16.9	21.4	19.8	18.4
8 k	14.8	17.5	16.3	15.4
16 k	14.1	18.4	16.6	15.8
Total (A)	32.1	35.1	33.9	32.9

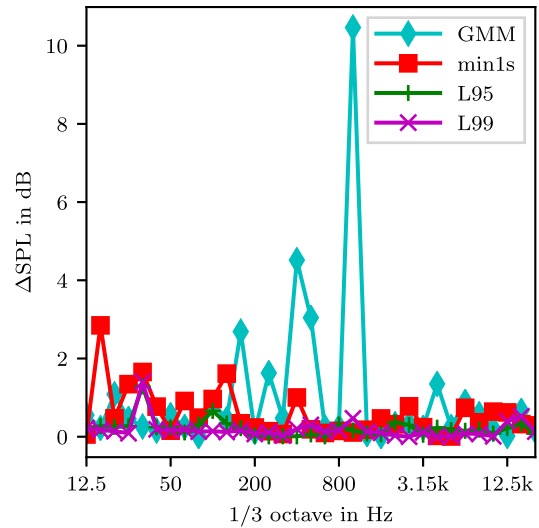


Fig. 10. Differences between two measurements of *Un Ballo in Maschera*.

of required levels from tenders [16] on the left and the measured levels of this study on the right. The total levels during drama performances (black circles) show the smallest scatter. The mean value of limits required in tenders somewhat corresponds to the levels that were measured in drama performances. For opera performances the comparison is less clear. While the very stringent min1s level also fits to the average of the tender requirements fairly well, a small change in the evaluation basis leads to a situation where the tender limits well exceed the determined  $L_{99}$  level.

4.6. Practical implications

Based on the discussion of the imperceptibility probabilities, it seems reasonable to distinguish between two scenarios.

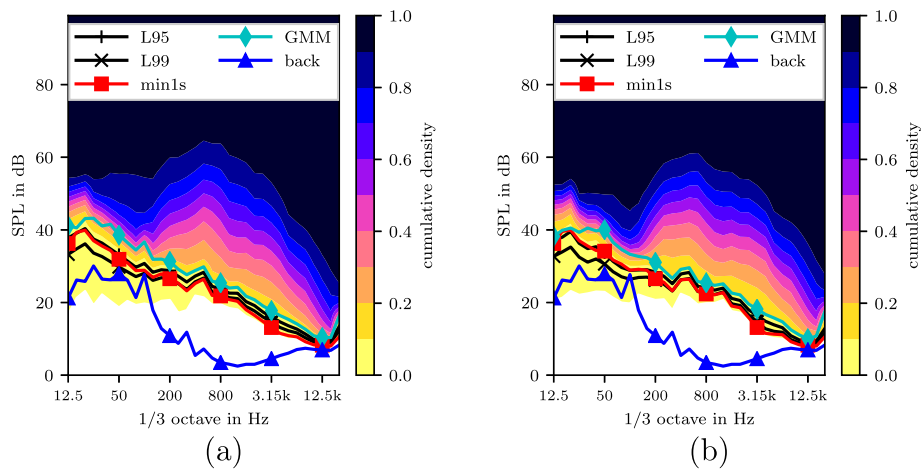


Fig. 9. Drama individual measurements and analysis results. (a) *Jeder stirbt für sich allein*, (b) *Amphitryon*.

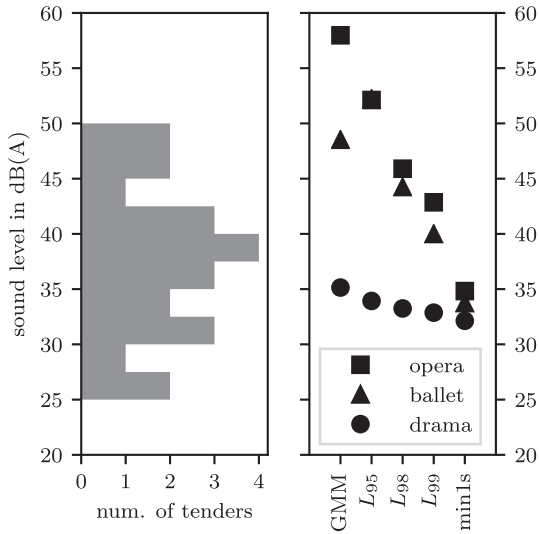


Fig. 11. Histogram of required levels from tenders [16] on the left and analysis method results (GMM,  $L_N$ , and min1s) applied on measured total levels on the right.

In standard environments, where a small chance to encounter audible stage machinery noise during a performance of approximately 0.03% is acceptable, noise limits based on  $L_{99}$  seem to be of practical use. To allow more artistic freedom and guarantee that the stage machinery is inaudible even throughout the quietest moments of a performance, min1s limits seem preferable in sensitive environments.

The limits for different art forms and sensitivities are shown in Fig. 12. For opera, the standard limits are illustrated by the red solid line and the sensitive limits by the magenta dashed line. In the case of ballet, the standard limit is given by the blue solid line and the sensitive limit by the cyan dashed line. Due to negligible difference between min1s and  $L_{99}$  limits for drama, only one noise limit needs to be specified. The numerical values are listed in

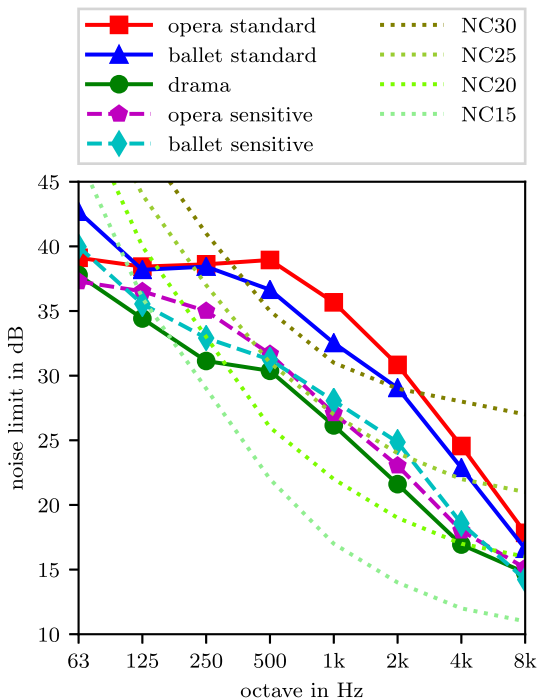


Fig. 12. Noise limits ( $L_{eq}$ ) for stage machinery in opera, ballet, and theater play in octave bands with NC-curves (dotted lines) in background.

Table 6. The values in brackets are close to the background noise level (see Figs. 5b, 6b, and 8b, blue solid line) and should be used with the proviso that they may not be suitable for very quiet environments. The total level limits in dB(A) are stated as supplemental information. As masking plays a significant role in noise perception, the spectral content is relevant and A-weighted total levels may not be of practical use.

4.7. Limiting factors

The number of investigated venues is limited by the challenge to get access to the middle of the first row during live performances with audience during day-to-day operation of a performing art venue. Comparison to other relevant publications [13,15,14,25] suggests that the sample size reported here is adequate and in many cases exceeds the number of investigated venues and recorded performances. Despite these efforts there is a lack of comparable (standardized) data that is generally available. As a result there is still a remaining theoretical chance of including outliers in the result. Ultimately, this probability can only be reduced by further investigations, which gradually lead to a comprehensive dataset. The drafting of a generally accepted measurement standard could be helpful in this endeavor. Taking the current state of knowledge into account, the presented results provide new insights into the levels during live performances in German venues. In the future, this measured data base can be extended by additional measurements including new venues on an international scale.

A potential limitation may be the lacking noise data of the operating stage machinery in the otherwise quiet hall. This limits the discussion to an assessment of likelihood whether the determined  $L_N$  levels are influenced by machine noise. Although impact seems rather unlikely, measured spectra would be preferable for a definite proof.

Eventually the findings of this study need to become subject to a perceptual evaluation. The perception of the machinery noise in the presence of continuous building service type sounds is a substantial investigation of its own and should be addressed in a future study. This study focuses on the technical description of performance sounds and can therefore provide a basis for perceptual evaluations to come.

As part of the probabilistic inaudibility discussion it was assumed that noise from the stage machinery is inaudible if it is of the same or lower level as other sounds that occur during a performance. This logic underestimates the ability of the human brain to separate multiple sound sources through binaural hearing. Binaural masking is currently difficult to quantify. New findings may

Table 6

Proposed noise limits ( $L_{eq}$ ) for opera, ballet, and theater play in octave bands (unweighted) and total level (A-weighted). Values in brackets are close to the measured background noise in investigated venues and should be adapted if necessary.

Octave Hz	Opera		Ballet		Drama dB
	Standard dB	Sensitive dB	Standard dB	Sensitive dB	
63 Hz	(39)	(37)	43	(40)	(38)
125 Hz	38	(37)	38	(36)	(34)
250 Hz	39	35	38	33	31
500 Hz	39	32	37	31	30
1 kHz	36	27	33	28	26
2 kHz	31	23	29	25	22
4 kHz	25	18	23	19	17
8 kHz	18	(15)	17	(14)	(15)
Total, dB(A)	43	35	40	34	32

warrant changing the employed relationship to better recognize the auditive sensitivity.

## 5. Conclusion

Based on measurements in 4 German performing arts venues involving 12 live performances with audience  $L_{min1s}$  and  $L_{99}$  have been identified as the most suitable criteria for requirements for stage machinery. The suitability discussion included the reproducibility of different criteria and their resilience against performance sound and stationary background noise. The results show the likelihood at which total levels occur under realistic conditions during performances of drama, opera, and ballet with audiences in octave and 1/3 octave bands ranging from 125 Hz–8 kHz. Understanding how likely levels at a given frequency occur in regular performances is relevant for the designers of stage machinery and technical directors. Producers of other stage equipment, architects, or musicians can also profit from these results.

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