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Investigation on acceptable reverberation time at various frequency bands in halls that present amplified music ☆

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ABSTRACT

Subjective ratings from 25 professional musicians and sound engineers were obtained to assess two Danish rock venues of similar size and similar low frequency reverberation times, but different high frequency reverberation times. The musicians judged one hall significantly better than the other, confirming a hypothesis that rock venues can have a longer reverberation time at mid to high frequencies at least in the empty condition. A fairly long reverberation time in the 63 Hz octave band is found to be acceptable, so the 125 Hz octave band is probably the single most important band to control for amplified music.

1. Introduction

Part of the perceived sound quality at any given indoor, amplified concert stems from the quality, extent, and tuning of the sound system, whereas another part stems from the acoustics of the hall. There has been limited scientific research effort published with the attempt to find recommendations for acoustics for amplified music concerts. A paper examined 20 Danish pop and rock venues, of which the acoustic conditions were measured and rated by musicians and sound engineers for halls of volume from approximately 1000 m^3 to 7000 m^3 [1]. From the study, the recommended reverberation time, expressed as $T_{30(63\text{-}2k)}$ for a given venue size, was suggested on the basis of sound engineers' and musicians' preference as one group. It was also found that the group of sound engineers in that particular survey preferred more dampened acoustics than the musicians, giving preference to the hall that had lowest reverberation time in the study.

It was further substantiated that what separates the best from the not so well liked venues is a shorter T_{30} in the 63 Hz, 125 Hz and 250 Hz octave bands. This finding is important, but actually not surprising, since bass levels are amplified to very high levels at pop and rock concerts, typically app. 100 dB(A) [2,9]. One paper [8] examined the sound pressure levels at various frequency bands for a large sample of popular recordings and found that the loudest level is found in the 125 Hz octave band. The level in the 125 Hz band was found to be about 5 dB(A) louder than the 63 Hz band. Similarly in [2] for actual live pop/rock concerts, it was found that the sound pressure level in the 125 Hz octave band was about 4 dB (A) louder than in the 63 Hz band whereas in another survey [9] the 125 Hz level was found to be in average 9 dB(A) louder than the 63 Hz level. Many instruments in a pop/rock band, including male vocal, play notes within the 125 Hz octave band with often quite syncopated rhythms. One sound is thus difficult to differentiate from another if the reverberation in this frequency band is too long. At loud sound levels, upward masking from this reverberant bass sound is quite broad [3].

This study first and foremost investigates whether it is plausible that the value of T_{30} in certain octave bands can differ from the suggested frequency independent values set forth in Ref. [1], with a particular interest in the 63 Hz band and the mid to high frequency range. This idea has already been postulated in a conference article [4]. Hence this present study is a continuation of the research carried out in [1,4], and the same methodology that was used in [1], collecting the subjective ratings on a 7-point scale, is applied here.

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2. Hypotheses

This article seeks to substantiate or reject the hypotheses presented below. All of these have previously been proposed in Refs. [2,4].

(1) Acousticians normally measure empty halls, whereas sound engineers and musicians experience occupied conditions. Halls where amplified music is presented often has no chairs. Due to a 4–6 times higher absorption coefficient by audience, seated or standing, at higher frequencies than at low frequencies [1], it is possible that a higher T_{30} at higher frequencies in the empty hall can be accepted. This leads to a more even T_{30} over frequency in the occupied hall.

(2) Due to the higher directivity of loudspeakers at higher frequencies compared to low, it is further possible that an increasing T_{30} with increasing frequencies might be acceptable even in the occupied hall. This hypothesis was exemplified in Ref. [5] from the perspective of the critical distance, and its dependency on the directivity Q. The equation for critical distance r_{cr}, as stated in [10], is reproduced as Eq. (1) below, where V is the volume of the hall, T, the reverberation time in this case including the audience, and α' is the average absorption coefficient of the room including audience.

$$r_{cr} = \sqrt{\frac{QV}{100\pi T(1-\alpha')}} \tag{1}$$

Since Q can easily be a factor of 5 higher at mid-high frequencies compared to low, for the critical distance to be constant at various frequencies, the reverberation time would have to be higher at mid-high frequencies compared to low. Evidently, such a space with increased T_{30} at higher frequencies will sound more live and the audience will be louder. It will also be easier for the musician to express dynamics [11]. In smaller clubs where the musicians' own instruments and open monitors, and not the PA sound system, is the main source of amplification, this broader tolerance of T_{30} would not apply.

(3) Sound in the 250 Hz band is more directive and is better absorbed by the audience than sound in the 63 Hz and 125 Hz octave bands [2]. Sound in both the 63 Hz and 125 Hz octave bands emerges often close to omni-directionally from the speakers, thereby reaching many surfaces in the room, adding up reverberation. However, it is likely that the reverberation time in the 63 Hz octave band can be longer than in the 125 Hz band due to the following effects:
According to[2,8,9], , sound levels are higher in the 125 Hz octave band than in the 63 Hz band, wherefore reverberation in the 125 Hz band will have a more significant spectral masking effect compared to reverberation in the 63 Hz band. The equal-loudness contours in the 63 Hz octave band are more densely spaced compared to the 125 Hz band, and the human ear is less sensitive in the 63 Hz octave band in general [3]. Perceptually, reverberation in the 63 Hz band possibly disappears faster than in the 125 Hz band and possibly masks less spectrally. The 63 Hz masking curve shows less upward masking than the 250 Hz band while the 125 Hz band is not listed [3].

The main aim of this article is to find answers to the hypotheses one and two, and loosely discuss the results in relation to the hypothesis three.

3. Method

25 musicians and sound engineers rated two Danish halls of similar volume: *Skråen* and *Magasinet*. The two halls have very similar low frequency T_{30}, while T_{30} at higher frequencies is significantly higher in *Magasinet* than in *Skråen*, as shown in Fig. 1, measured in empty state and in Fig. 2 including a standing audience calculated with absorption coefficients from [1].

3.1. The two halls

To the best knowledge of the authors, there is only one hall in Denmark, *Magasinet* of 2700 m^3, which has a controlled T_{30} in the 125 Hz octave band and a relatively high T_{30} at mid- and high frequencies. In this hall, reverberation is controlled exclusively by means of membrane absorption, placed in the entire ceiling area and on a big wall area behind the stage. The hall has little high frequency absorption, limited to sparsely distributed textiles on stage and upholstered chairs on the balcony level.

The other venue, *Skråen* of 4000 m^3, has porous absorption in the entire ceiling and on the back wall, by means of suspended wooden fiber elements. *Magasinet* was renovated in 2008, while *Skråen* moved to new premises in the same year.

3.2. Subjective survey

The administrators of the two halls informed the authors which bands had regularly performed in their venues within the last 5–6 years. A link to an on-line questionnaire was e-mailed to the relevant musicians and sound engineers it was possible to contact. Of the 25 people who answered the survey, 11 were sound engineers and 14 were musicians. The choice to make the questionnaire anonymous was made so as to render as much freedom to the test persons as possible. By coincidence, none of the musicians who participated in the previous survey [1] were involved in this present survey. It is uncertain whether any of the eleven sound engineers had also participated in the survey presented in Ref. [1].

The on-line survey started with a group of general questions: what monitoring do you use? how important is the acoustics in the venue for you? (rating 1: not at all/rating 7: very important), do you sometimes chose not to play certain venues on the account of the acoustics? These questions could not be left unanswered in the survey. Then, each of the two halls could be rated on four different parameters on a seven-scale: Clarity bass (rating 1: muddy/rating 7: clear), Clarity mid/treble (rating 1: muddy/rating 7: clear), Reverberation mid/treble (rating 1: too dead/rating 7: too lively – rating 4: optimal), and General rating (rating 1: very poor, rating 4: reasonable, rating 7: excellent). At the end of the questionnaire,

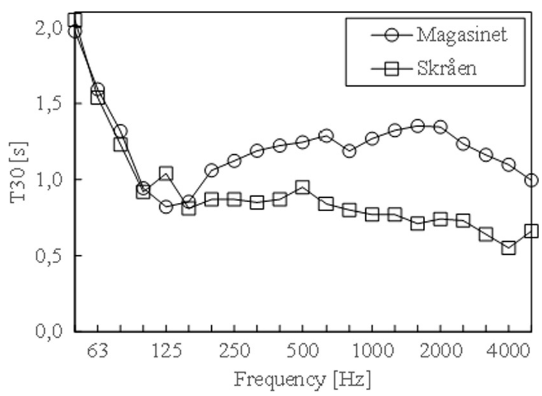

Fig. 1. T_{30} of the two venues, *Magasinet* and *Skråen*, in the empty condition.

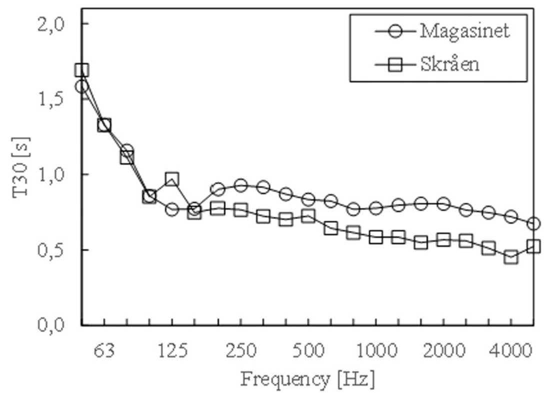

Fig. 2. T_{30} of the two venues, *Magasinet* and *Skråen*, including audience calculated with absorption coefficients from [1].

the test person was asked to write whatever he/she deemed of importance regarding acoustics for amplified music.

4. Results and discussion

4.1. First part of the questionnaire

14 musicians answered the questionnaire: two lead singers, five guitarists, one keyboard player, three bass players, and three drummers. In response to the question: "*how important is the acoustics in the venue for you?*", the average of eleven sound engineers' ratings was 6.6 out of 7, while the average of 14 musicians' answers was 5.9. It is unknown how many musicians got the questionnaire and chose not to answer it. It cannot be ruled out that the musicians who do not deem acoustics so important are not eager to answer this type of questionnaire. Of the 14 musicians, seven use in-ear monitors. Six of those who use in-ear monitoring also use open monitor speakers. Both lead singers reported that they sometimes chose not to attend venues on account of the acoustics. Only three musicians and four sound engineers answered positively to this question. It is plausible that the lead singer often takes such decisions when booking the tour. On the question regarding to what extent in-ear monitors can help mitigate the possible bad effects of a hall's acoustics, the musicians' average answer was 4.6 out of 7, whereas the sound engineers' average response to this question was 5.5. These results are in agreement with the findings in Ref. [1].

4.2. Analysis of the ratings

In order to find evidence for the hypotheses mentioned, a linear mixed model and Analysis of Variance (ANOVA) are attempted to explain the subjective ratings S_{ijk} in Table 1. The subjective rating is expressed in the following form:

$$S_{ijk} = A + \alpha_i + Bj + Ck + D\delta_{jk} + \varepsilon_{ijk}, \tag{2}$$

where i is the subject, j is the concert hall ($j = 0$ for *Magasinet*, and $j = 1$ for *Skråen*), and k is the occupation of the respondent ($k = 0$ for musicians and $k = 1$ for sound engineer) [6,7].

The fixed effects are written with upper case Latin characters (A, B, C and D) and the random effects are written with Greek characters (here only α_i). δ_{jk} is the Kronecker delta function that explains an interaction between the two factors, the hall and occupation. The random effect is regarded as a normally distributed stochastic variable with zero mean and standard deviation, σ_α. The residual or unexplained variation, ε_{ijk}, is also assumed to be normally distributed with zero mean. The choice of the mixed model is based on the assumption that a considerable amount of the variance in the observations is dependent on inter-subject differences, so the subject is regarded as a random effect. However, this inter-subject effect is found to be much smaller than the residual term, so the final model is constructed without the α_i term. Significant differences are found only for the general rating (GR) and the bass clarity (BC), and their final regression models are found to be

$$GR_{ijk} = 5.55 - 1.55j - 1.21k + 1.41\delta_{jk} + \varepsilon_{ijk}, \quad R = 0.41. \tag{3}$$

$$BC_{ijk} = 5.45 - 1.03j - 1.01k + 0.38\delta_{jk} + \varepsilon_{ijk}, \quad R = 0.46. \tag{4}$$

From Eq. (2), we can see that the musicians' general rating is averaged to 5.55 for *Magasinet* ($j = 0$), and sound engineers' rating is 4.0 for *Skråen* ($j = 1$). Similarly, the bass clarity is 5.45 for *Magasinet* and 4.42 for *Skråen*. For these two ratings, the sound engineers' responses are lower than the musicians' by about 1, on average. From Eqs. (2) and (3), it is proven that the halls are significantly different regarding the general rating and bass clarity with p values of 0.012 and 0.037, respectively.

For the general rating, a 2-way ANOVA, which does not take into account the respondents as a random effect, gives a significant variation using the hall (*Magasinet* or *Skråen*) as the factor (∗significance, $p = 0.044$). However, there was no significant variation depending on the occupation (musician or sound engineer) as the factor ($p = 0.31$), or including the interaction between hall and occupation condition ($p = 0.12$). Using only the musicians' responses, an ANOVA analysis shows a p-value of 0.0066 (∗∗ significance), which indicates that the musicians rated Magasinet significantly better than Skråen in the overall rating. This result supports hypothesis one and two. Both lead-singers have rated *Magasinet* "7", while rated *Skråen* "1" and "3". One of them commented that he would recommend future halls to be acoustically similar to *Magasinet,* supporting hypotheses 3 and 4. More lively mid-high acoustics with more vivacity makes the performer hear the audience better, whereby the communication and the exchange of energy between band and audience are enhanced. This is particularly important for the lead-singer who forms a "bridge" between the band and the audience. Further, the musician can express dynamics easier. Using only the sound engineers' overall rating, the two halls are not significantly different ($p = 0.915$).

The bass clarity is found to be significantly different depending on the hall and occupation with p-values of 0.025 and 0.031, respectively. This is surprising since the actual reverberation curves for the 63 Hz and 125 Hz regions are almost identical, which may indicate that mid to high frequency reverberation could possibly mask low frequency reverberation.

Significant differences between the two halls for the Clarity mid/treble rating, are not found. It should be noted that once the audience enters a hall like Magasinet, mid/treble reverberation decreases significantly as shown in Fig. 2, so that such a venue probably is perceived with a suitable, high degree of clarity in the mid to high frequency domain.

5. Conclusion

Among two pop/rock music venues with a similar T_{30} at low frequencies yet quite different T_{30} at high frequencies, *Magasinet* with the higher T_{30} at mid-high frequency, has been rated significantly better among the musicians than *Skråen*. This is an indication that mid-high frequency reverberation can be longer than the reverberation in the low frequency bands in the empty hall. The fact that the bass clarity at *Magasinet* is rated decent, despite a very high T_{30} in the 63 Hz band, could indicate a high tolerance toward a high T_{30} in the 63 Hz band as long as T_{30} in the 125 Hz band is controlled. Therefore, it is likely that the 125 Hz octave band is the

Table 1
Individual ratings of the two halls. SE means a sound engineer.

	Magasinet				Skråen			
	Clarity bass	Clarity mid/treble	Reverb mid/treble	General rating	Clarity bass	Clarity mid/treble	Reverb mid/treble	General rating
SE	–	–	–	–	–	–	–	6
SE	5	3	6	3	3	1	6	2
SE	3	5	4	4	3	4	4	4
SE	3	5	5	4	5	4	4	5
SE	5	3	3	5	4	6	4	7
SE	7	7	4	7	1	5	4	1
SE	6	5	3	5	4	4	5	3
SE	3	5	6	3	4	4	5	4
SE	–	–	–	–	4	5	5	–
SE	3	3	5	3	6	6	4	6
SE	5	5	5	5	4	4	4	4
Average	4.4	4.6	4.6	4.3	3.8	4.3	4.5	4.2
Guitar	6	6	6	6	6	6	6	6
Guitar	5	5	4	6	4	4	3	3
Guitar	–	–	–	–	5	5	5	5
Guitar	5	5	5	5	5	5	5	5
Guitar	5	5	4	4	4	4	3	4
Drums	5	5	5	5	4	5	5	–
Drums	5	5	5	5	4	4	4	4
Drums	5	6	–	5	4	6	4	4
Bass & gtr.	6	6	4	6	6	6	1	2
Bass	–	–	–	–	4	–	–	4
Bass	5	5	5	5	6	6	6	6
Keyboards	–	–	–	–	5	5	4	5
Vocal	7	7	7	7	2	2	1	1
Vocal	6	6	4	7	3	3	2	3
Average	5.5	5.5	4.9	5.6	4.4	4.7	3.8	4.0

most important frequency band to control for amplified music. Furthermore, the difference in the rating of the bass clarity between the two halls, despite their similar T_{30} in the 63 and 125 Hz bands, indicates that long reverberation at mid-high frequencies can mask excessive low frequency reverberation.

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