ACOUSTICS IN SMALL MUSIC ROOMS - EVALUATION OF SUBJECTIVE RATINGS AND LOW FREQUENCY RESPONSE

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1 INTRODUCTION

Acoustic quality in small rectangular rooms has been the subject of many investigations in the search for optimum room dimension ratios. Among some of the notable contributors are Sabine[1], Volkman[2], Bolt[3], Louden[4], Walker[5], Cox and D'Antonio[6], Meissner[7] and Rindel[8].

In rooms smaller than 300 m^3, the so-called "Schroeder's limiting frequency", can be approximately 200 Hz or even higher, depending on the reverberation time and room volume[9]. Below the Schroeder frequency, the density of room modes is low and there is not statistically diffuse distribution of room modes thus the frequency response of the room will be uneven. For a music room this means that many musical tones will not be supported at all whereas others will be reinforced by the room. For musical instruments, the evenness of the tones throughout the whole register of the instrument is of great importance. If we consider the music room as an extension of the instrument, it would be logical to think that the frequency response of the room also should be as equal, or smooth, as possible, as suggested by Rindel[10,15].

The hypothesis of this paper is that a music practice room has better acoustical performance when the low frequency response is smooth. The importance of a smooth frequency response is undisputed for sound studios and control rooms[8], however there are no known studies in the acoustical literature that can provide evidence for the importance of a smooth low frequency response for small music practice rooms based on subjective responses. This means that it is not known to what extent a musician can perceive the difference between an even or uneven distribution of the lowest natural modes in a music practicing room.

In a study about sound quality in small rooms for speech or music, Weisser and Rindel[11] found that there was an increased subject sensitivity to very low frequency bands, ranging from 50 to 100 Hz. This is relevant for the hypothesis since the low frequency responses of the rooms mainly focuses on a frequency range below the lowest playable limit of the most common musical instruments.

Sandaker[12] performed a study where six music practicing rooms were evaluated by professional musicians or music students. Sandaker compared subjective ratings of the acoustic qualities of the rooms to measurements and simulations of several room acoustic parameters.

Bolt[3] suggested a method to assume the frequency response based only on the room geometry; Frequency Spacing Index (FSI). It applied only to rectangular rooms. Rindel[15,16] suggested a method to describe modal reverberation time and distribution of musical tones in nearly rectangular rooms.

In a study by Berg[13], the global frequency response between 20 Hz and 200 Hz was measured and calculated for several small music rooms. Measurements of small rooms with rigid and sloped walls showed that the frequency shift for the affected modes was relatively small compared to predictions made based on mean dimensions of the rooms. In small rooms with sloped walls, where one or more walls were non-rigid, the measured frequency responses deviated much more from the predicted natural frequencies and frequency responses. It was suggested that the "non-rigidness" of the walls, or phenomena such as acoustic transparency, transmission or phase shift due to wall impedance explains the deviation between measurements and predictions, rather than the angling of the walls.

In this paper, the room dimensions from Sandaker's study have been used to calculate the Frequency Spacing Index (FSI) for the 25 first room modes, as well as the smoothness of the global frequency response between 20 Hz- 200 Hz. Since the rooms have sloped walls, the mean dimensions of the rooms are being used in the calculations. The calculated FSI and frequency responses are then compared to the subjective ratings of the rooms from Sandaker's investigation.

2 FREQUENCY RESPONSE OF A ROOM AT LOW FREQUENCIES

2.1 Natural frequencies of a rectangular room

The solution to the wave-equation[14], given in the equation below, yields the natural frequency of the mode with the modal number (n_x, n_y, n_z), or eigenfrequencies, of a rectangular room with the dimensions l_x, l_y, and l_z and the speed of sound, c.

$$f_n = \frac{c}{2}\sqrt{\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2} \tag{1}$$

2.2 Frequency Spacing Index (FSI)

The frequency spacing index (FSI) is a measure to evaluate the frequency distribution of the room modes. Bolt[3] first used this criterion to evaluate the room acoustic quality at low frequencies for approximately 25 consecutive modes in the low-frequency region, with lower and upper limiting frequencies depending on the room volume. Walker[5] used a similar index based on all modes up to 125 Hz which also means the method is volume dependent. Rindel[8,10] suggested instead using the 25 first, or lowest, room modes as a quantitative measure of the room acoustic quality at low frequencies. Independent of room volume. The formula for calculating the FSI $\psi(n)$ is shown in equation 2.

$$\psi(n) = \frac{1}{f_n - f_1}\sum_1^{n-1}\left(\frac{\delta^2}{\bar{\delta}}\right) \tag{2}$$

The average frequency spacing is $\bar{\delta} = \frac{f_n - f_1}{n-1}$ where f_1 is the frequency of the first mode, f_n is the frequency of the mode number n and δ is the frequency spacing; the frequency difference between one mode and the previous one. This method is intended to apply only to rectangular rooms.

The FSI should be as low as possible. Theoretically, and unrealistic, the ideal is ψ = 1, corresponding to perfectly equal spacing of the room modes. Rindel[8] and Meissner[7] have pointed out that the lowest possible FSI for a real room is ψ = 1.3 obtained for the aspect ratio (1:1.20:1.45).

2.3 Global frequency response

The distribution of the room modes is also evaluated by calculating the global frequency response between 20 Hz and 200 Hz. The global frequency response is calculated by placing the source and receiver in opposite corners to include all room modes. The calculation method used is a modal energy analysis model by Rindel[15,16].

The model requires various variables; room dimensions, absorption coefficient of the surfaces, angling of the walls and roughness of the walls (based on a scattering-model). Thus, it is not limited to strictly rectangular rooms with rigid walls.

A best-fit regression line for a 2nd order polynomial is then calculated based on the global frequency response as a criterion for smoothness. This criterion was also used by Meissner[7] as a criterion for the smoothness of the frequency response.

2.4 Small room bass ratio (SBR)

The Small room bass ratio (SBR) was suggested by Weisser and Rindel[11] as a parameter to describe the boominess and boxiness of small rooms in listening situations to music or speech. The parameter is reported to correlate very well with the subjective results. The SBR is defined using the one-third-octave bands T_{30} values as shown in equation 3.

$$\mathrm{SBR} = 10\log\left[\frac{T_{30}(63\ \mathrm{Hz}) + T_{30}(80\ \mathrm{Hz})}{T_{30}(250\ \mathrm{Hz}) + T_{30}(315\ \mathrm{Hz})}\right]\mathrm{dB} \tag{3}$$

3. THE MUSIC PRACTICING ROOMS

In the study by Sandaker[12], six rooms were evaluated. Four of the rooms were situated in a music school in Askim, outside of Oslo, and two of the rooms were situated at Oslo University. The four rooms in Askim were evaluated by four participants working as music teachers representing the flute, classical guitar, clarinet and snare drum. The two rooms in Oslo were evaluated by three music students representing the tenor saxophone and classical guitars (two). The rooms chosen for the study in Askim were not the same as those normally used by the music teachers. This was to avoid issues due to the participants knowing one of the rooms from earlier use.

For this article, the different rooms have been numbered one to six for practical reasons, where room no. 1 - 4 are in the music school in Askim, and room no. 5 - 6 are at Oslo University.

3.1 Subjective rating of the rooms

The rooms were evaluated based on questions related to three main categories for each room.

The first was called room acoustic parameters, with questions about reverberation time, timbre, clarity, balance (high-low), balance (room-instrument), carries well, details, motivation, different position.

The second category was about overall characteristics and quality of the room acoustics, with questions about; “good acoustics”, “help play”, “sharp”, “boomy”, “metallic”, “visualize”, “come back”. The third was questions about how the room influenced the playing; “change play”, “change timbre”. It was also asked if the change of play or timbre was important or not.

On the questions regarding the quality of the room acoustics, and the rooms’ usability as rehearsal rooms, the participants were asked to judge whether the room had good acoustics, help the test subject to play well, and whether they want to come back and rehearse in the room as often as possible. In table 2, the column “overall rating” shows the order in which the rooms were judged by these three questions. Number 1 means first place, in other words the best ranking of the rooms, and 4 means fourth place, or the worst of the rooms.

The participants were at the end asked to rank the rooms in their preferred order, from what room they liked most to the one they liked the least. The mean value of the ranking of the rooms are shown in table 2, under the column “rank”.

Sandaker noted that, when comparing the results of the questions regarding the quality of the room acoustics and the rooms’ usability as rehearsal rooms, it was evident that the rooms were rated in the same order as when asked directly which room they prefer, which led to the conclusion that the results therefore were reliable.

3.2 Findings from the study

The main findings of Sandaker are that rooms with short reverberation time, especially EDT, and high clarity, C_{80} or T_s seem favorable. Sandaker also concludes that it is of importance that the different parameters are uniform over frequency. It is also pointed out that highly irregular amplitudes over time and frequency are disadvantageous.

The evenness of the reverberation time curves is investigated and compared to the tolerances given in ISO 23591:2021[17]. Three out of six rooms in the study lie within the tolerances for evenness of the reverberation time for quiet and loud acoustic music. Only room no. 1, 2 and 4 lies within the acceptable tolerances according to ISO 23591:2021 for the 1/1-octave bands 125 Hz – 4000 Hz. The measurements are limited to the 125 Hz 1/1-octave band as the lower limit.

In general, there seems to be a trend of the questionnaire answers that the rooms are rated higher on “Good acoustics”, “Help play”, “Visualize” and “Come back”, whenever the sharp, boomy and metallic sounds are rated low. The musicians report timbre changes as important, only when they perceive a positive timbre change of their instrument. Reverberation time is rated as the most important acoustic parameter and the possibility of hearing details in the music is rated quite high, indicating that the Clarity parameter (C_{80}) seems to be an important parameter characteristic of the rooms.

3.3 Room geometry

The hypothesis is based om the assumption that *nearly rectangular* rooms can be evaluated as if they were rectangular by using the average room dimensions. Room no. 1 is quite far from rectangular but is included in the evaluation, nevertheless. The average room dimensions, volume, reverberation times and calculated Schroeder frequencies are shown in table 1. The EDT_{mid} and $T_{30, mid}$ are the mid-frequency values, averaging the results at 500 Hz and 1000 Hz.

Table 1: Average room dimensions, volume, measured EDT and T_{30}, and calculated Schroeder frequency, f_s, for room 1-6.

Room no.	Volume (m^3)	l (m)	w (m)	h (m)	EDT_{mid} (s)	$T_{30, mid}$ (s)	f_s (Hz)
1	55.1	5.48	4.02	2.50	0.29	0.38	166
2	58.8	7.70	3.04	2.51	0.30	0.45	175
3	43.3	5.44	3.15	2.51	0.30	0.34	177
4	43.7	5.23	2.93	2.86	0.40	0.53	220
5	26.6	4.47	2.53	2.35	0.30	0.34	226
6	29.4	4.90	2.52	2.38	0.31	0.33	212

Figure 1 shows the two-dimensional room shape seen from above. The floor and ceiling of the rooms are parallel to room no. 1 - 4 (i.e. no angling), whilst room no. 5 and 6 have a slightly angled ceiling. For room 1, the sketch has added lines showing average room dimensions of the rectangular shape used for the calculations.

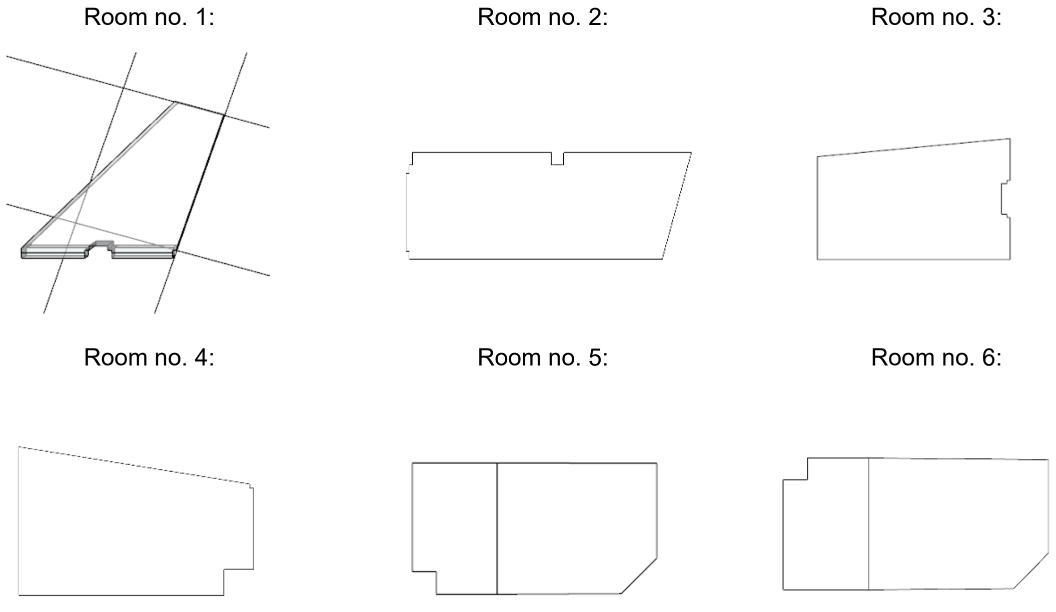

Figure 1: 2D-views of room 1-6. The sketch for room 1 shows added lines marking the average room dimension used. The figures are not in scale.

4. RESULTS

The calculated frequency spacing index (FSI) and the smoothness of the low-frequency responses are presented in table 2, together with overall rating and aspect ratios *l/w* and *w/h* of the room dimensions. The smoothness is defined by the best-fit regression line for a 2nd order polynomial of the calculated global transfer functions.

Figure 2 shows the calculated global frequency responses from 20 Hz – 200 Hz together with the best-fit regression line for a 2nd order polynomial. In addition, the *Small Room Bass Ratio* (SBR) has been calculated from the measured impulse responses (analyzed in 1/3 -octave bands, T_{30}) for the rooms, and the result is presented in table 2.

The results show that the room that the musicians liked the best has the lowest FSI, and that of all rooms investigated, there was a correlation between FSI and subjective rating. The correlation is valid also for the smoothness of the low-frequency responses of the rooms, defined by the best-fit regression line for a 2nd order polynomial of the calculated global transfer functions.

Table 2: Aspect ratios l/w and w/h, subjective rating, calculated FSI, 2nd order polynomial of the transfer functions and SBR for room no. 1 - 6.

Room no.	*l/w*	*w/h*	Rank	Overall Rating			FSI	R^2	SBR (T_{30})
				Good acoustics	Help play	Come back			
1	1.36	1.61	1.25	1	1	1	1.60	0.80	2.2
2	2.53	1.21	2.50	2	2	2	2.10	0.69	1.9
3	1.73	1.25	2.50	3	3	3	2.17	0.62	2.2
4	1.78	1.02	3.75	4	4	4	2.69	0.55	1.1[a]
5	1.77	1.08	1.00	1	1	1	2.40	0.60	0.5
6	1.94	1.06	2.00	2	2	2	3.01	0.54	0.8

Note a: T_{20} is applied instead of T_{30}

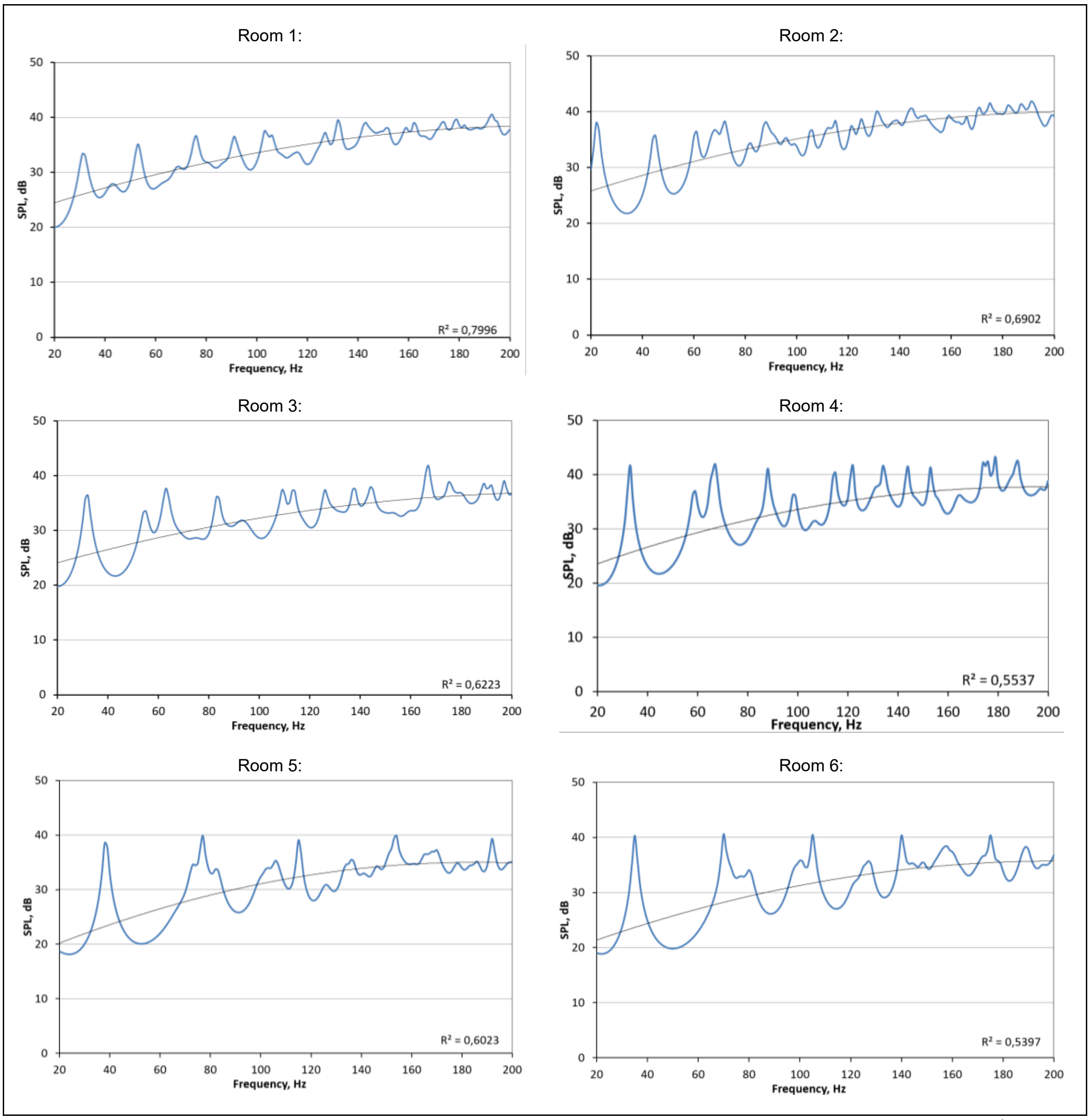

Figure 2: *Calculated global frequency responses and best-fit regression lines for a 2nd order polynomial for room 1-6.*

Figure 3 shows the calculated aspect ratios *w/h* and *l/w* for the six rooms in a contour-plot of FSI for the 25 first room modes, $\psi(25)$. The figure shows areas of values with good FSI (low values $\psi \leq 1.6$) and poor FSI (high values $\psi > 1.8$).

It is worth mentioning that only room no. 1 lies within the recommended intervals 1.15 < *l/w* < 1.45 as stated in Annex B of ISO 23591[17]. Room no. 1 lies close to the ideal areas in the contour-plot of FSI as a function of aspect ratios. Room no. 2 has a *l/w*-relation as high as 2.53 and would not fulfil the criteria on room ratios in the standard. The contour-plot shows interestingly that there is another area where the room dimensions seem to be favorable, and room no. 2 lies on the edge of this area. Thus, rooms 2 and 3 having very different dimension ratios, have approximately the same FSI, and they were subjectively evaluated almost identically. This is a further support to the hypothesis that FSI is a usable measure for the acoustic quality of music rehearsal rooms.

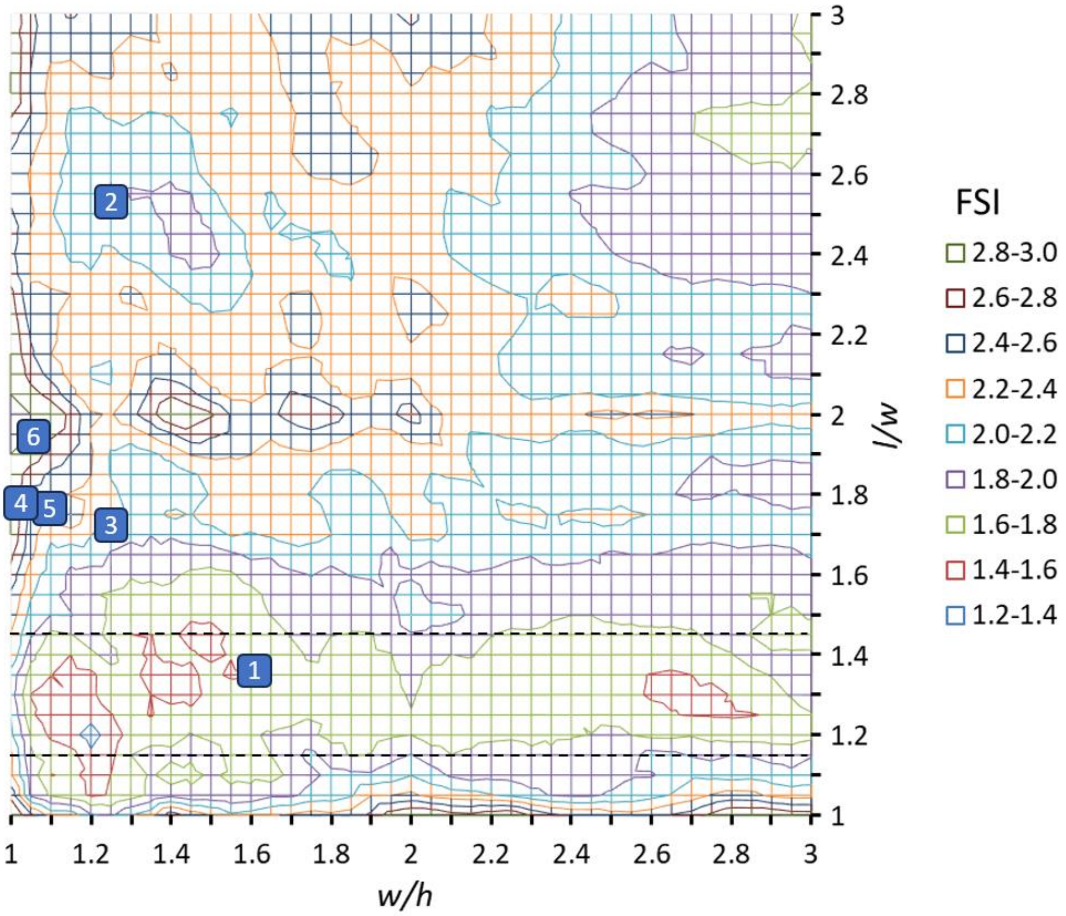

Figure 3: Contour-plot of FSI ψ (25) as a function of aspect ratios w/h and l/w. Inside the blue and red regions where ψ (25) ≤ 1.6, the distribution of the modes is very good. The six rooms are plotted according to the dimension ratios. The dashed lines show the recommended l/w-intervals (1.15 < l/w < 1.45) as stated in the ISO 23591:2021.

3 CONCLUSION

The hypothesis of this paper, that a music practice room has better perceived acoustics when the low frequency response is smooth, seems to be supported by the results when comparing subjective ratings to FSI as well as the criterium for the smoothness of the low global frequency responses for the investigated rooms. The hypothesis is further supported by the fact that room no. 2 has a *l/w*-ratio far from the recommendation in ISO 23591:2021 but lies close to an area with lower values of FSI.

However, the question remains whereas to what degree a musician can perceive the room responses at frequencies, especially lower than the lower limit of the instrument being played. This is further investigated using the parameter SBR (Small room bass ratio). The analysis of the impulse responses in 1/3- octave band does not show any corresponding values to the subjective ratings and SBR. The measurements in the 1/1-octave band 63 Hz might have been of insufficient quality, or the perceived boominess can't solely be explained by the reverberation time in third-octave bands. SBR could perhaps be an indication of perceived warmth, which could be a positive and wanted quality.

Interestingly there is a greater correlation between the FSI and the subjective rating than for reverberation time (T_{30}) and frequency dependent tolerance curves as stated in the ISO 23591:2021[17]) for small practicing rooms. Most of the rooms have relatively smooth reverberation time curves from 125 Hz – 4000 Hz, and three of the rooms are within the given tolerances in the standard. It is important to point out that the fact that most of the rooms were designed for, and acoustically treated for music, has allowed a comparison by analyzing the low frequency properties of the rooms. It is also worth pointing out that there is a correlation between the ratings and the calculated Schroeder limiting frequency for room no.1 - 4.

The number of rooms and musicians responding to the questionnaires are unfortunately quite few hence a statistical conclusion is not possible. Also, the inclusion of bass instruments and bowed string instruments would be wanted. Nevertheless, the findings in this study could be a basis for further studies of music rehearsal rooms on a larger scale.

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