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Musicians' impressions of low frequency sound field in small music rooms

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Abstract
A recently implemented standard BSI EN ISO 23591:2021 constitutes a basis to specify acoustic quality criteria for music rehearsal rooms and spaces which also includes an indication of the room resonances in such rooms. This paper aims to contribute towards the clarification of the effect of resonances on a musicians' perception and the perceptual differences related to instrument sound power level. To analyze the low frequency environment and related distortions, 2 selected rooms were measured and simulated by the wave-based simulation method for modal analysis, and then 24 musicians were interviewed with a performance-based questionnaire. In order to investigate the resonance perception, the musicians' data was gathered through face-to-face interviews analyzed by quantitative analysis. In both rooms, the overall impression is highly correlated with reverberance and loudness. However, when resonances are audible, the perceived reverberance and loudness are altered by the resonances and clarity becomes prominent. For the detection and evaluation of resonances, The Quality-Factor and Modal Decay Time threshold values are applicable; however, the threshold values may be higher for rehearsal conditions than listening conditions.

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Keywords
Performance-based questionnaire, Room resonances, Small music room, Subjective evaluation, Wave-based simulation.

1. Introduction

In small music rooms such as music classrooms, practice rooms, rehearsal rooms and chamber rooms, the sound environment is highly under the influence of low frequency related sound behavior (Beranek, 1962; Kleiner, 2014; Kuttruff, 2009; Olson, 1967; Toole, 2008). The physical properties of the room, depending on its size, bring along many acoustical defects (D'Antonio, 2017). The wave interaction of the direct and reflected sound arriving from closed boundaries causes variation in the sound pressure level at any point in the sound field and forms a non-diffuse sound field (Cox & D'Antonio, 2004). At the same time, modal resonances occurring due to small volume create energy concentration in particular frequencies which results in a change in timbre of the perceived sound (Gade, 2015). In contrast to timbre change caused by the loss of some mid or low frequency ranges, repetitive frequency response fluctuation result as coloration (Kleiner, 2014). Besides this, a large sound power in combination with a small room volume results in loud sound and may cause loudness disturbance and hearing impairment because of the high sound pressure levels that musicians are exposed to while rehearsing (Phillips, 2008; J. Royster et al., 1991). These types of rooms also have a rectangular shape, which brings about echo problems as well (Løvstad, 2003). On the other hand, mostly applied sound absorptive treatment as a solution to these problems leads to a change in timbre, reduced support, and shorter reverberation times (Kleiner, 2014).

As well as the physical dimensions and acoustic characteristics of the room, the physical characteristics of the instruments is also very significant in terms of perception (Kato et al., 2010). Many studies show that the potential sound power that can be generated by the instrument, the frequency range of the instrument, and the type of instrument itself (wind, string, percussion etc.) should be taken into consideration when designing the rooms (Riduan, 2010).

According to Schroeder theory which specifies a cross-over frequency as a transition range from the modal region to the statistical region (Schroeder & Kuttruff, 1962), due to the wave behavior of sound, the use of geometrical acoustics is limited below the statistical region (Savioja & Svensson, 2015). It has also been revealed from the measurement and simulation comparison studies that the transition is higher than the cross-over frequency determined by the Schroeder theory since the theory neglects the source boundary interference (Dance & Buuren, 2013).

A very recent standard BSI EN ISO 23591:2021 (British Standards Institution, 2021) has been launched to specify acoustic quality criteria for music rehearsal rooms. According to this standard, these types of rooms are divided in accordance with music types (quiet-loud-amplified) and user type (individual - medium - large ensemble). Along with the division, optimum Reverberation Time (RT) and volume ranges are described. In addition to these parameters, the standard addresses the room resonances and suggests optimum room ratios to eliminate the room resonances. However, in such rooms, more information is needed to describe and guide how resonances should be evaluated when related to room design considerations.

The purpose of this study is to investigate the effect of a low frequency environment on perceptual attributes regarding room resonances. Principally, a performance-based questionnaire was presented to musicians after performing in two small music rooms, both having different sound environments in terms of mode occurrences and Reverberation Time. The questionnaire results were examined with regards to correlations between perceptual attributes related with acoustical defects occurring in small rooms, and additional analysis was performed on general level rankings of instrument sound power level and the attribute responses. The objective parameters such as Early Decay Time (EDT), Reverberation Time (T20, T30), Clarity Index (C20, C50), Centre Time (Ts) and Early Support (STearly) were obtained from the measurements. In order to assess the effect of mode related problems on

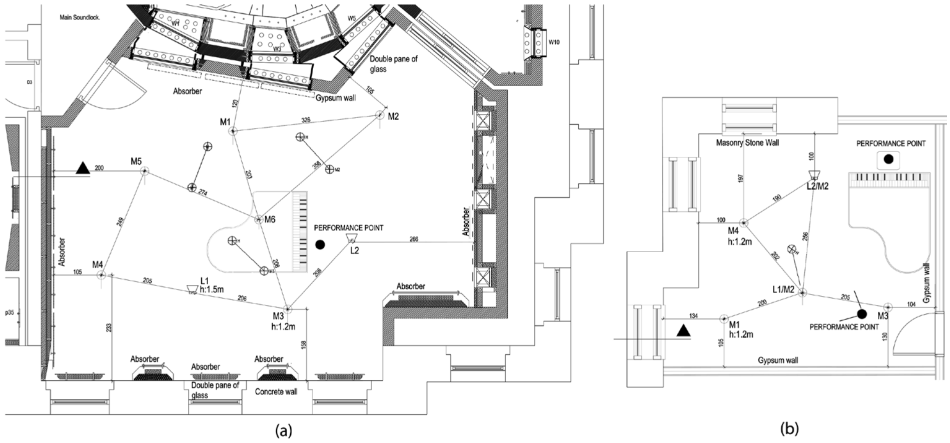

Figure 1. *a) Studio room plan; b) music teaching room plan.*

the low frequency environment, the frequency response obtained through measurements was evaluated through Quality Factor (Q-Factor) and Modal Decay Time. In addition to the spectral analysis and decay time parameters, the wave-based finite element simulation method was introduced through which modal analysis was conducted in order to visualize and evaluate the effect of modes on the low frequency environment.

2. Methodology

2.1. Description of rooms used in the study

In this study, two rooms with different acoustical conditions were selected for the individual practice or rehearsal for unamplified music: the live room of a recording studio, and a music teaching room, both situated in Istanbul Technical University - Erol Üçerler Advanced Music Research Center (MIAM). Since the studio room is used for recording purposes, sound absorbing systems are used extensively in this room to control strong reflections, and the room was designed with non-rectangular geometry as a plan scheme for the modal solution. The net area of the studio room is $57m^2$ and its net volume is $296m^3$ with a net average room height of 5.2m. The plan of the studio room is shown in Figure 1(a). In addition to the partially applied sound absorptive systems, the studio room has parquet on the floor, façade windows, windows overlooking the control room and other iso-booths as reflective surfaces. The second room, which is used for rehearsal and teaching purposes, has a rectangular plan scheme and an acoustic environment with much more reflective compared to the studio room. The area of the teaching room is $29m^2$ and net volume is $103m^3$ with the net height of 3,5m. The plan of the teaching room in which the study was conducted is shown in Figure 1(b). Except for the rock wool panels used on the ceiling, no absorption system was used on the lateral surfaces or on the floor. These two rooms were chosen because of their different resonance occurrences and levels of reflection.

2.2. Objective measurements and parameters

2.2.1. Objective parameters used in the study

In this study, parameters such as early decay time (EDT), Reverberation Time (T20, T30), Clarity Index (C20, C50), Centre Time (Ts) and Early Support (STearly) were measured to objectively explain the acoustic conditions in the rooms. Due to the small physical dimensions, there is a much lower reverberation time in small rooms compared to performance halls. Although reverberation is a basic parameter in the analysis of rooms, different explanators stand out in non-diffuse rooms due to irregularity in frequencies as a result of modal behaviors. Although there is no clear distinction between the low and high frequency response of the room, theoretically the Schroeder frequency is used for this distinction. The Schroeder frequency is based on mode density in relation to room volume and modal damping which is calculated by the following relation (1) with the metric system definition (Schroeder & Kuttruff, 1962).

$$f_s = 2000\sqrt{\frac{T_{60}}{V}} \qquad (1)$$

Where:

- f_s = Schroeder frequency (Hz)
- T_{60} = Reverberation time (s)
- V = Volume (m^3)

Modal spacing and density has often been a basic indicator and an objective measure to quantify the quality of the acoustic environment in small rooms. Modal theory reveals that, the modes get closer as the volume and frequency increase thereby increasing the intensity of the mode. As the mode intensity increases, the total amplitude in the frequency response flattens and a more diffuse sound field occurs (Fazenda & Wankling, 2008). Due to the relationship of these modes with the physical dimensions of the room, researchers have proposed optimal room ratios regarding the modal density with the aim of avoiding modal degeneracy. Bolt criterion is based on modal frequency distance with little bunching of modes for optimum room ratio (Bolt, 1947). According to Gilford, in order not to detect axial modes, the maximum distance should be 20 Hz (Gilford, 1958). In the criterion that Bonello proposed, the number of modes placed in each octave band must be the same or more than the previous one, the maximum distance between the modes should be less than %5 of the mode frequency and modes must not overlap (zero spacing) (Bonello, 1981).

The Quality Factor is a criterion that evaluates the effect of peaks and dips occurring in frequency response on perception according to the shape of the mode. The presence of peaks and dips modify the overall sound for the listener by altering the amplitude at certain frequencies. Furthermore, the Q-Factor of these peaks and dips are also associated with decay times for a particular frequency. In comparison, the flattest response, corresponding to a lower Q-Factor, results in the shortest decay time and in general the more homogeneous frequency responses (flat) are associated with shorter time responses (Fazenda & Wankling, 2008). The Q-Factor is calculated according to the relation (2) below which calculates the ratio of the center frequency to the frequency difference below 3dB (Noxon, 1986). Studies into the detection of resonances at lower frequency were carried out by Olive, at frequencies between 63 and 500 Hz and the main results indicated that, using pink noise as the test signal, the detection thresholds decrease as the Q-factor increases. It was also shown that for broadband steady state signals, detection worsens as frequency decreases with the exception of lower Q resonance detection, which appears to be independent of frequency (Sean et al., 1997). Additionally, listening tests investigating the relationship between the Q-Factor and perceptibility reveals that Q16 is the threshold for the listening environment (Stephenson, 2012).

$$Q = \frac{f_c}{\Delta f}, Q = \frac{f_c}{Bw\ mode} \qquad (2)$$

Where:

- Q = Quality factor
- f_c = Peak frequency
- *Bw mode = f2-f1*

f2 and *f1* denotes the 3dB lower frequency of the peak frequency. In addition to the level changes in frequencies, the decay time of those frequencies are also effective in the detection of the modes. For this reason, the Modal Decay Time in the frequencies where the modes are active is calculated indirectly by the following relation (3)(Prato et al., 2016).

$$T_{modal} = \frac{2.2 \times Q}{fc} \qquad (3)$$

Where:

- T_{modal} = Modal decay time (s)
- Q = Quality factor
- f_c = Peak frequency

When the relationship between Modal Decay Time and modal threshold is investigated by subjective tests using different stimulation types, studies show that the threshold increases towards lower frequencies and the detection of modes changes due to the stimulation type (Fazenda et al., 2015).

2.2.2. Measurement set-up

In each room, Reverberation Time and related decay time parameters were measured according to BSI EN ISO 3382-1 (British Standards Institution, 2009) and BSI EN ISO 3382-2 (British Standards Institution, 2008) using DIRAC 4.1 Type 7841 simulation software (Acoustics Engineering, 2007). Since the limit of 300m³ specified in the standard as the limit for small room volume, BSI EN ISO 3382-2 was also used as the measurement procedure in both rooms. The C curvature parameter was checked for the measure T_{20} and T_{30}, since the non-linearity of the curve formed due to the modes in small rooms would have a negative effect on the reliability of the results due to multiple slopes. In these measurements, a B&K type 4296 omnidirectional loudspeaker was used as the source, the B&K 2260D sound pressure level meter and omni microphone were used as the sound receiver system. Since it is necessary to produce a minimum 45dB higher sound pressure than the background noise during the measurements, the sound source is connected to the B&K 2716 type sound power amplifier. A logarithmic sweep sine signal was used in the measurements since it is less sensitive to background noise and time variance (Bjor & Nikolic, 2004). To increase precision, each measurement was made twice independently and the prepass was set to 10 as it is defined in the related standard. The placement of the loudspeaker (L1, L2) and microphone points (M1, M2, M3, M4, M5, M6) used in the measurement of the decay time parameters and Support (ST_{early}) parameter are shown in Figure 1.

2.2.3. Simulation set-up

In the COMSOL program, which has frequently been used in eigenfrequency analysis of small rooms (Ayr et al., 2017; Schmalle et al., 2011), the rooms were modeled in a CAD environment and imported, and eigenfrequency analysis was made in accordance with wave theory. An essential factor in terms of the accuracy of the simulation is to determine the optimum mesh size according to the smallest wavelength (λ). The smallest mesh size (d) used in the study is determined in accordance with $d \leq \lambda/8$, as it has been suggested in previous studies investigating the optimum mesh size (Papadakis, 2017). The degree of freedom (DOF) of the studio room and music teaching room are 781642 and 367725 respectively. Increasing the mesh size increases the precision of the system and affects the simulation duration as well as the computer load as well. The wave equation used in eigenfrequency analysis is as in the formula (4) (COMSOL Multiphysics, 2018).

$$\nabla.\left(-\frac{1}{\rho_c}\nabla \mathrm{p}\right)+\frac{\lambda^2 \mathrm{p}}{\rho_c c^2}=0\ ,\ \lambda=\mathrm{i}2\pi\mathrm{f}=i\omega \quad (4)$$

Where:

- p_c = Density of medium
- p = Pressure
- λ = Wavelength
- c = Speed of air
- f = Frequency
- ω = Angular frequency

2.3. Subjective evaluations and questionnaire procedure

Musicians' subjective evaluations towards each room were obtained through a performance-based questionnaire which aimed at evaluating the acoustic conditions that the musician perceives during solo performance particularly, in terms of perceived resonances, reverberance, clarity, loudness, bassiness, naturalness, and support. The questionnaire was prepared following the recommendations and examples from certain specific literature. Firstly, general guideline publications were referred to regarding stage enclosures (Dammerud, 2009), performance rooms (Lokki et al., 2012) and listening rooms (Kaplanis et al., 2019) , which aim to settle a common framework to enable consistent survey results. However, since there are very few survey studies on this topic, the questions and terms gathered from the related references were adapted for in rehearsal purpose. The questions looked at the musician's preferences on bipolar semantic differential scales (Likert rating scales) ranging 1–5, and also included open-ended questions explaining the musician's evaluations about the room and the effect of the room on their performance.

Table 1. *Instrument classification and participant distribution according to instrument type.*

Instrument	Sound power (Forte - mW)	Sound power level (dB re 1 pW)	Power spectrum classification[a]	Frequency Range (Hz)	Number of Participant
Grand piano	10,0	100,0	Loud	28-4186	6
Cello	1,0	90,0	Quiet	65-988	2
Acoustic Guitar	0,4	86,0	Quiet	82-1397	2
Violin	0,8	89,0	Quiet	196-4186	2
Saxophone tenor	6,3	98,0	Loud	104-659	3
Double bass arco	1,6	92,0	Quiet	41-247	1
Bassoon	2,0	93,0	Quiet	60-620	1
Trombone	25,1	104,0	Loud	60-500	1
Clarinet	2,0	93,0	Quiet	165-1568	3
Trumpet	12,6	101,0	Loud	165-988	1
English Horn	10,0	100,0	Loud	110-880	1
Flute	1,3	91,0	Quiet	262-1976	1

[a]As specified in the standard ISO 23591:2021, the non-amplified instruments are divided into two groups according with their music generation; quiet music with sound power levels lower than 95 dB, and loud music higher than or equal to 95 dB at forte.

The study was limited to two rooms (one with room resonances, and one without room resonances) in order to provide a subtle and noticeable controlled evaluation environment (Toole, 2008). Classical music with a similar dynamic range and tempo was the general music genre used during the solo performances, though there were no specific restrictions to the type of piece. Studies investigating the difference in perception created by different test samples have shown that the use of different music samples has not been specifically relevant in sound field evaluations for low frequencies (Park & Jeon, 2016; Shtrepi et al., 2015; Wankling & Fazenda, 2009). In addition, to test the rooms, chromatic scales were played with the instruments in order to minimize the possible effects between different selections of musical pieces. Musicians started with the warmup session which is crucial for room adaptation as well as for instrument tune up. After playing parts of a musical piece lasting for a minimum of 1.5 minutes twice, musicians were asked to fill in the guided questionnaire in the studio room and in the music teaching room respectively. After the musicians were given a short introduction to explain the study's parameters, musicians completed the questions immediately after performance due to the nature of short acoustic memory. The participants consisted of 15 males and 9 females, including MIAM students and academicians, whose experiences varied between 8 to 35 years. The average age of the participants was 28 (SD 6.6). Instrument distribution and properties, which were used for the classification of instrument types as for data reduction, are given in Table 1. The instruments' sound power level data gathered for the division is listed in the standard BSI EN ISO 23591:2021, however, there are different values specified in Meyer's research for the grand piano example which is also mentioned in the related standard in the dip notes (Meyer, 2009).

3. Study

3.1. Room measurement and simulation results

The acoustical parameters described in the BSI EN ISO 3382-1 (British Standards Institution, 2009) standard, that is, Early Decay Time (EDT), Reverberation Time (T*20,* T*30*), Clarity Index (C*20*, C*50)*, Centre Time (T_s) and Early Support (ST*early*), were obtained from the IRs measured at each receiver position. Average and standard deviation of the parameters are introduced between 63-1000 Hz in Table 2. T_{60} measurement results are not available at 63 Hz since the signal-to-noise ratios are not high enough due to the low frequency generation of the loudspeaker used in the measurements. However, the T_{30} decays are available at 63 Hz with a signal-to-noise ratio of NR ≥ 35 dB. The degree of the curvature of the decay curves were also checked and the values are higher than zero, although there are values very close to zero due to small room dimensions (British Standards Institution, 2008). When the standard deviation of parameters in all octave bands are examined, it is seen that it decreases towards the

Table 2. *Parameters measured according to ISO 3382 in studio room and music teaching room.*

Room	Objective parameters	Frequency in 1/1 octave bands (Hz)									
		63	St. Dev	125	St. Dev	250	St. Dev	500	St. Dev	1000	St. Dev
Studio room	EDT (s)	0,52	0,21	0,44	0,11	0,39	0,13	0,37	0,07	0,40	0,06
	T_{20} (s)	0,61	0,08	0,58	0,08	0,43	0,05	0,39	0,04	0,41	0,02
	T_{30} (s)	0,62	0,05	0,59	0,05	0,44	0,03	0,40	0,03	0,41	0,02
	C_{20} (dB)	1,33	2,93	1,18	3,35	1,34	4,55	2,73	1,98	1,86	0,99
	C_{50} (dB)	4,39	3,03	5,44	2,54	7,92	2,8	9,16	2,08	8,11	1,21
	T_s (ms)	45,2	11,1	42	7,6	28,8	10,4	22,1	5,5	23,9	3,1
	ST_{early}(dB)	-3,03	1,44	-6,06	1,24	-7,3	1,14	-8,08	0,9	-6,5	0,73
Music teaching room	EDT (s)	0,58	0,16	0,64	0,10	0,63	0,13	0,44	0,08	0,40	0,07
	T_{20} (s)	0,82	0,16	0,86	0,09	0,76	0,08	0,63	0,06	0,59	0,06
	T_{30} (s)	0,82	0,14	0,87	0,07	0,81	0,07	0,69	0,06	0,67	0,06
	C_{20} (dB)	-1,34	2,12	-1,82	2,78	-0,18	1,85	1,85	2,7	1,87	1,22
	C_{50} (dB)	3,15	3,39	3,65	1,91	4,46	1,96	7,26	1,85	7,87	1,1
	T_s (ms)	54,8	15,1	51,7	7,2	42,6	8,7	29,1	7,7	26,9	3,7
	ST_{early}(dB)	-3,14	1,13	-3,36	0,91	-4,3	1,06	-2,98	0,99	-4,11	1,19

upper octaves as an indicator of the increase in diffusivity in the room. Generally, EDT values are expected to be close to T30 with a deviation 5% for optimum conditions (Bradley, 2010), however, the EDT values are very small due to close source-receiver positions. Also, the initial part of the decay has more deviation compared to the late part of the decay, since early reflections are not homogeneous due to room modes and interference with absorptive and reflective surfaces close to the measurement points. Since reverberation time is a basic indicator, BSI EN ISO 23591:2021 specifies the optimum ranges for T_{mid} (average value of 500 Hz and 1000 Hz) depending on net volume and type of music. As expected, the T_{mid} value of the studio room does not satisfy the criteria, however, the Tmid value of the music teaching room satisfies the criteria both for quiet and loud music. Also, the frequency-dependent tolerance limits for the highest and lowest reverberation times relative to mid-frequency at each octave (T_{30}/T_{mid}) are specified in the related standard. Accordingly, the percentage of the ratio at 63Hz and 125Hz is higher than the tolerance limits (p_{63Hz}=%155>%140, p_{125Hz}=%147>%120, p_{250Hz}=%108<%110) in the studio room. Whereas the ratio at 63Hz, 125Hz and 250Hz lies within the specified limits in the music teaching room (p_{63Hz}=120<%140, p_{125Hz}=%127=%120, p_{250Hz}=%119=%110). The Clarity Index (C_{20}) results indicates a lack of clarity in the music teaching room, whereas clarity is high (C_{20} exceeds 3dB) in the studio room. The STearly parameter was also measured to quantify the self-support of the room during the rehearsal. Although there are similar values at 63 Hz in both rooms, it is seen that the values are lower in the studio room compared to the music teaching room at higher octave bands. For the objective measurement of bassiness, bass ratio based on Reverberation Time can be examined, and the values are 1.2 and 1.3 for the studio room and music teaching room respectively. As the main contributor towards the perception of proximity, the initial time delay (ITD) obtained from the impulse response of the selected receiver point (performance point) in the studio room is 11,5ms with a relative amplitude of -11,5 dB when floor reflections are excluded which arrives approximately 3ms after direct sound. The ITD value of the selected receiver point in the music teaching room is 6ms with a relative amplitude of -0,02 dB when the floor reflections are excluded similarly. Also, the Sound Strength (G) of the rooms was estimated in accordance with room volume and Tmid as specified in the standard BSI EN ISO 23591:2021. The estimated G level of the studio room is 13 dB and when L_p(forte) is preferred to be between 85-90 dB, most of the instruments such as cello, acoustic guitar, violin, double bass, bassoon, clarinet, and flute were under preferred limits. Meanwhile, since the G level of the music teaching room is 22 dB, grand piano, trombone, trumpet, and

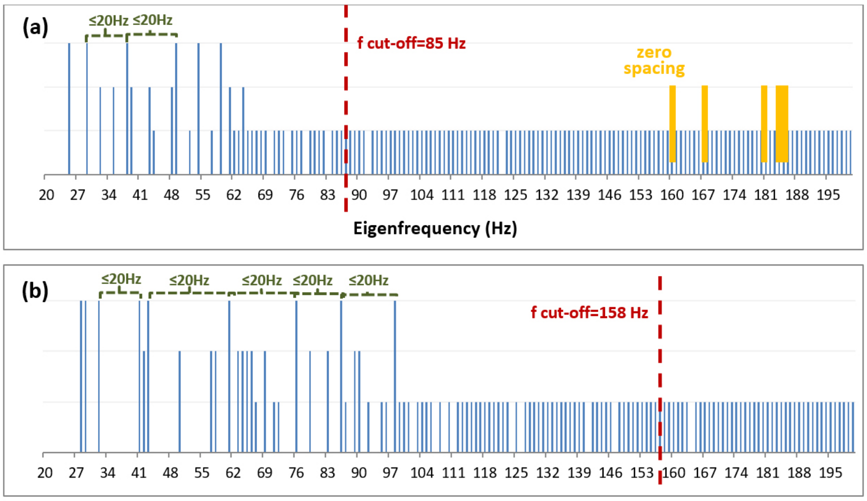

Figure 2. *Comparison of mode distribution in the a) studio room; b) music teaching room.*

English horn were above the preferred limits.

As defined in the BSI 23591:2021, to achieve a smooth frequency response in the bass range, it is desirable to have a favorable proportion between room dimensions, especially in rooms smaller than 300m^3. According to preferable frequency response, the ratio w/h is restricted to the range 1,2 to 1,6 and the length-to-width ratio should preferably be in the interval 1,15 < l/w < 1,45. The studio room has dimension ratios within the given ranges (l/w=1,28 and w/h=1,2), however, the music teaching room does not provide the optimum ratios since the height is not the smallest dimension of the room (rockwool ceiling is excluded) and the room dimension ratio is close to 1:1:1. Nevertheless, optimum room dimensions eliminate the occurrence of resonance but do not change the audibility of resonances, which is basically dependent on the location of the source-receiver and boundary conditions.

In this study, for the modal analysis of the rooms, the COMSOL5.3a simulation program (Educational type) was used, through which eigenfrequency values were calculated and visualized. The mode distribution and the mode density were examined between 20-200 Hz (Figure 2). The Schroeder frequency as the cut-off frequency was calculated as 85 Hz in the studio room and 158 Hz in the music teaching room. The damping and volume are lower in the music teaching room; therefore, the transition frequency comes up to a higher band according to Schroeder theory. As the mode distribution of the music teaching room is examined, it is seen that, the distance of modes exceeds 5% mode distances and there is a bunching of modes up until the transi-

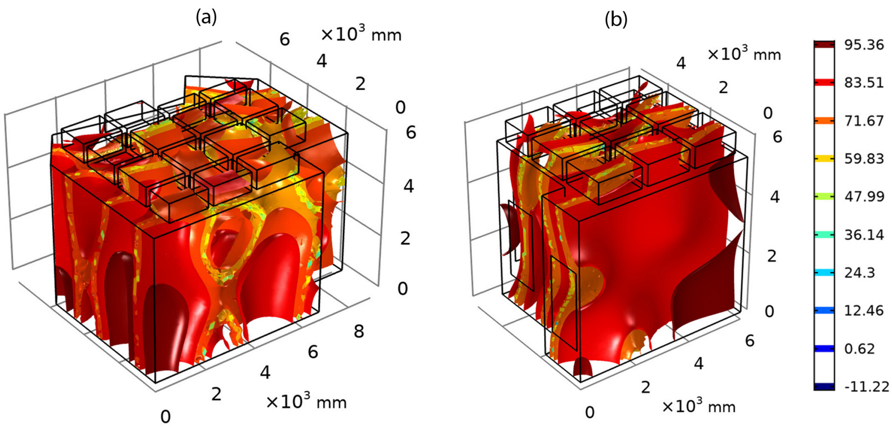

Figure 3. *Sound pressure level distribution in rooms at 98 Hz a) studio room; b) music teaching room.*

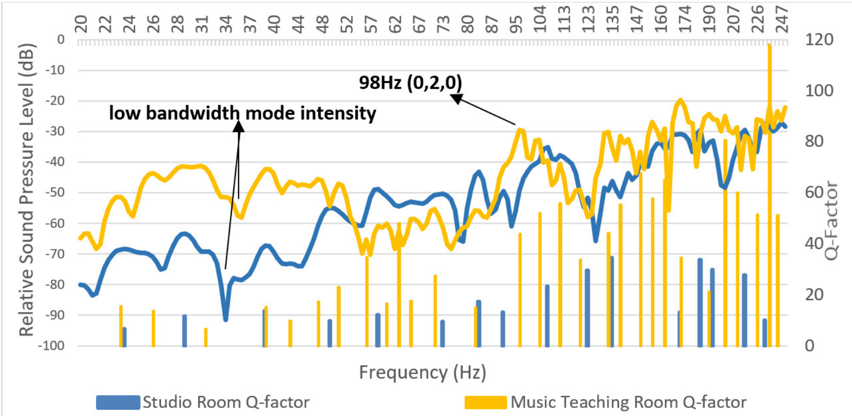

Figure 4. *Comparison of frequency response obtained from the measurement and Q-Factor evaluation of these responses.*

tion frequency. The Gilford criteria is satisfied in both rooms when the axial modes are examined. In the studio room, above the cross-over frequency, zero spaced modes occurred, however they can be neglected since there are 3 modes in those bands.

The comparison of SPL distribution of eigenfrequency obtained from the simulation at 98 Hz for both rooms is shown in Figure 3 as an example of mode effect on the SPL distribution. With the increasing volume and irregularity at the boundary, a much more distributed sound pressure is provided, whereas in the music teaching room with a cuboid dimension, the axial modes can be observed even at 98 Hz (0,2,0), which normally occurs at lower frequency ranges.

For further low frequency analysis, frequency response measured at the participant's location (L2-M6 at studio room, L1-M4 at music teaching room) in both rooms were evaluated through Q-Factor between 20-250Hz (Figure 4). Unlike the modal analysis, the Q-Factor, which is the audibility of the resonance, is highly dependent on source-receiver interference and surface conditions. When the receiver is located at the antinode region, mode occurrences becomes observable. As an example, the axial mode (0,2,0) occurred at 98 Hz caused a peak, whereas the low mode intensity caused a dip in the frequency response as well. As a result of spectral analysis, the obtained Q-Factor in the studio room is almost below Q30, whereas the values exceed Q30 in the music teaching room, particularly between 100-250Hz. In both rooms the Q-factor values are higher than the Q16 threshold value which was obtained through previous subjective listening tests (Stephenson, 2012).

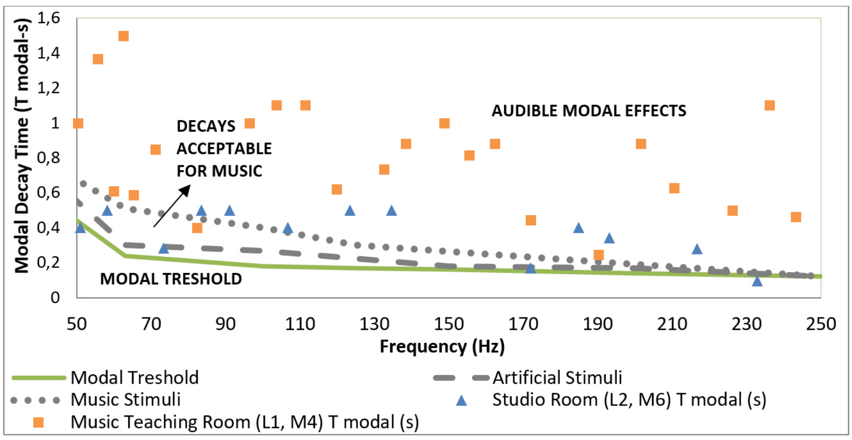

Figure 5. *Comparison of Modal Decay Time obtained from the measurement in the given receiver locations (Drawn after Fazenda (Fazenda et al., 2015).*

It is important to relate the objective data with the perceptual attributes when evaluating the sound environment. The study investigating the perceptibility of modes conducted by Fazenda (Figure 5) showed that the threshold curve between 50-250 Hz, which is dependent on the stimuli type, decreases towards higher frequencies. The Modal Decay Time values at the participant points for both rooms are indicated in Figure 5. The Modal Decay Time values obtained from the Q-Factor in the studio room exceed the limit by a very small amount, whereas the values in the music teaching room drastically exceed the threshold.

3.2. Room perceptions

Musicians playing different instruments performed the same piece in both rooms, and then filled out 5-point Likert scale type questionnaires to evaluate the acoustic conditions. The results were analyzed in IBM SPSS statistics v27 (IBM SPSS Statistics, 2020). Figure 6 shows the perceptual attributes in the two different rooms, along with their mean value, based on subjective parameters such as perceived reverberance, support, loudness, resonance, naturalness, and overall impression. Perceived reverberance was defined as "reverb time, tail length in time" and the question offered the responses between (1) *low* and (5) *high*. In the questionnaire musicians were asked to assess perceived support (defined as the level of the room support while playing their instrument) and the questionnaire offered responses between (1) *playing alone and* (5) *strong support*. Loudness was defined as 'overall impression of the room loudness' and the questionnaire offered the responses between (1) *low* and (5) *high*. Naturalness (*1-artificial / 5-natural)*, which is usually used for the assessment of reproduction rooms, was used as an indicator of timbre perception in the small room. Resonances were defined as "feel of resonating tones" and the offered responses were between *(1) none and (5) strong*. The results showed that, loudness, support, reverberance and perceived resonances were given higher scores by participants in the music teaching room, whereas the naturalness scored lower. When the participants were asked about the overall impression in the rooms, the studio room scored higher than the music teaching room with a close mean value. Varying instrument types could also affect the results; hence, further analysis has been done to analyze the effect of different instrument characteristics on the preferences.

In subjective evaluations, the relationship between parameters can differ along with the room characteristics. Non-parametric Spearmen rank correlation analysis was run to examine the relationship between parameters and to analyze which of the parameters were prominent on the overall impression. The correlation analysis results of the studio room are shown in Table 3 and the music teaching room results are shown in Table 4. The attributes introduced in the table are basically categorized into two groups, the evaluation of the room response, and the room's effect

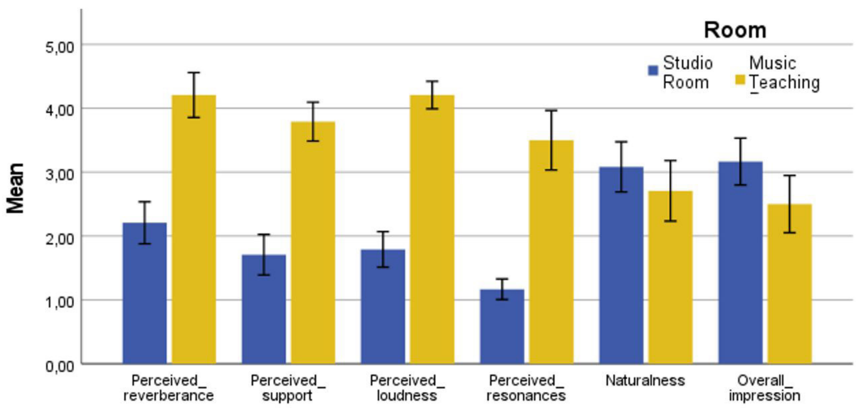

Figure 6. *Mean values of the subjective parameters.*

Table 3. *Spearmen's rank correlation between subjective parameters in the studio room (*p< 0.05, **p<0.01). OI: Overall impression nformation about the sample group departments.*

	1	2	3	4	5	6	7	8	9	10	11	OI
1.Perceived reverberance	-	-0,284	0,201	**,436***	0,179	0,273	0,106	0,278	0,258	**-,411***	**-,566****	**,593****
2.Perceived clarity			-0,024	-0,035	-0,134	-0,035	-0,145	-0,118	-0,186	**-,502***	-0,252	0,023
3.Perceived support				**,577****	0,137	0,327	0,168	**,456***	0,319	-0,179	-0,052	0,258
4.Perceived loudness					0,350	**,502***	0,150	**,713****	0,223	0,040	-0,243	**,512***
5.Perceived resonances						-0,349	0,009	**,448***	**,497***	-0,097	-0,199	0,102
6.Naturalness							**,418***	**,461***	-0,183	-0,076	-0,315	**,456***
7.Bassiness								0,163	0,131	-0,030	0,233	0,119
8.Room effect on performance									0,162	-0,021	-0,189	**,532****
9.Loudness disturbance										0,029	0,000	0,081
10.Unable to focus											**,408***	**-,422***
11.Difficulty in dynamic changes												-0,303

on the performance.

According to correlation analysis of the studio room, reverberance showed a positive correlation with loudness and had a negative correlation with difficulty on dynamic changes and focusing during the performance. This indicates that a lack of reverberance, as well as excessive reverberance, may also cause performance problems. Perceived clarity (*1-muddy, 5-clear*) affected the performance since it caused problems with musicians' focus during rehearsal. Loudness, which is associated with the level of reflection, is positively correlated with support and naturalness. It is the most prominent attribute on performance with the highest correlation coefficient. Even though the room has precautions in terms of resonance problems (such as absorption panels on the wall), the audibility of resonance, which is positively correlated with loudness, can still be perceived arriving from singular reflective surfaces (such as control room windows or iso-booth windows) and it has been observed to have an influence on performance. Since the perceived resonance is very low in the studio room, no significant relationship could be found between perceived resonance and other parameters. Bassiness was defined as 'amount of bassiness, both aural and in feeling' and the question offered responses between (1) *low* and (5) *high*. It is also positively correlated with naturalness; therefore, the lack of bass tones caused the room to be perceived as artificial. Consequently, due to the room conditions, reverberance, loudness, and naturalness are the parameters which describe the overall impression the most.

In the music teaching room, the cor-

Table 4. *Spearmen's rank correlation between subjective parameters in the music teaching room (*p< 0.05, **p<0.01). OI: Overall impression.*

	1	2	3	4	5	6	7	8	9	10	11	OI
1.Perceived reverberance	-	**-,573****	0,342	**,586****	**,557****	**-,428***	0,231	0,167	0,378	**,531****	0,156	**-,641****
2.Perceived clarity			-0,230	**-,656****	**-,654****	**,727****	-0,184	-0,218	**-,575****	**-,667****	-0,257	**,638****
3.Perceived support				**,496***	**,450***	-0,134	0,196	0,242	0,338	**,449***	**,468***	-0,230
4.Perceived loudness					**,790****	**-,631****	0,059	**,663****	**,636****	**,777****	**,621****	**-,743****
5.Perceived resonances						**-,684****	0,085	0,353	**,607****	**,772****	**,462***	**-,630****
6.Naturalness							-0,269	-0,399	**-,661****	**-,661****	**-,554****	**,668****
7.Bassiness								0,033	0,244	0,311	0,100	-0,041
8.Room effect on performance									**,417***	0,278	**,476***	**-,435***
9.Loudness disturbance										**,643****	**,427***	**-,411***
10.Unable to focus											**,495***	**-,731****
11.Difficulty in dynamic changes												**-,516****

relation coefficient and the correlated attributes are higher due to a high level of reflections. The perceived reverberance is negatively correlated with clarity as expected, and results in focus problems. It also has a negative correlation with naturalness, which indicates that reverberance over the optimum value causes the room to be perceived as artificial. Support is positively correlated with loudness and negatively correlated with performance related attributes. Loudness, as the most descriptive attribute, showed a strong correlation with almost all parameters. Perceived resonances are positively correlated with loudness and changes the naturalness. Bassiness is the least correlated attribute in the music teaching room and the correlation with resonances is very low. When the performance related attributes are examined, it is observed that the room has an impact on the performances and overall impression. Consequently, due to the room conditions, reverberance, clarity, loudness, naturalness, and resonances are the parameters which mostly describe the overall impression.

By means of Fisher's exact test rxc contingency table (Mehta & Patel, 2010), this study examined whether the room perception changed due to certain instrument characteristics such as sound power level (Lw). The statistical results found that there is a significant interaction between instrument sound power level and perceived loudness (*p=0,019, two-sided Fisher exact test*), loudness disturbance (*p=0,012, two-sided Fisher exact test)* and clarity (*p=0,003, two-sided Fisher exact test)* in the music teaching room in which the instrument group with high Lw were disturbed by the excessive loudness and were not able to hear the sound clearly. In the music teaching room, perceived reverberance was higher in the group with high Lw (*p=0,006, two-sided Fisher exact test)* whereas there was no discrimination in the studio room since the reverberation time is low for all instruments. In the studio room, the naturalness was perceived natural in the group with low Lw, whereas it was perceived as artificial by the group with high Lw (*p=0,003, two-sided Fisher exact test*). In the music teaching room, there was no significant difference since most of the musicians evaluated the room as artificial (*p=0,15, two-sided Fisher exact test*). The perceived resonance (*p=0,001, two-sided Fisher exact test*) was high in the group with high Lw in the music teaching room, whereas there was no discrimination in the studio room since almost none of the musicians felt disturbed by the resonances. Like the other attributes, there is a clear distinction between quiet and loud instrument types where the overall impression is low for the loud music instruments in the music teaching room (*p=0,009, two-sided Fisher exact test)*.

Significant data was also obtained in this study from the open-ended questions in the questionnaire, where participants were asked how the room response was and how it affected their performance. The answers to the open-ended questions and reported comments were manually coded and similar themes were grouped. Since the reverberation time obtained objectively in the studio room is lower than the limit range, the participants' comments focused on the lack of reverberance and spatial impression. In the music teaching room, resonance related problems at low frequencies and shrillness problem at trebles were repeatedly mentioned. Also, both sound environments negatively affected the performance by causing exhaustion, focus problems, and a change in tempo and dynamic level during the rehearsal

4. Discussion

Low frequency behavior in small rooms is always a critical issue, with the effect of resonances changing the perceived environment by altering the time response and spectral content. The findings are discussed in terms of the measured room response and the relationship with subjective parameters through which the performance-based survey was conducted in the tested rooms. The optimum values and JND values of the objective parameters are essential to define the influence of physical changes and comparison of sound fields, however, the values are defined in limited frequency ranges for limited parameters (Bradley, 2010; British Standards Institution, 2009). Moreover, recent studies suggest higher JND values for the parameters such as Clarity Index (Vigeant et al., 2015) and Early Decay Time (Dorrego & Vigeant, 2020). For this reason, there is a need to determine the JND values at low frequencies under small room conditions for the interpretation and evaluation of the results (Vorländer, 2013).

For the design of rehearsal rooms, the recent standard BSI EN ISO 23591:2021 has been introduced specifying the optimum RT and volume ranges according to instrument sound power level and loudness. In this study the findings were consistent with the related standard since the most descriptive parameters for the tested room conditions obtained were: perceived reverberance and loudness. The measurement results which showed consistency with the musicians' expressions were objectively assessed as specified in the standard in terms of reverberation time, including low octave bands and loudness for different types of instrument involved in the study. Based on the measurement results and survey results, it was inferred that, T30 in the studio room was below the recommended ranges with the use of wide band absorbers, where the musicians were not satisfied. On the other hand, T30 in the music teaching room is within the limited ranges with ±10% tolerances, however, with the effect of resonances T30 was perceived as higher than normal with instruments that have a high sound power level. Similarly, the resonances had a clear impact on the perception of clarity in the music teaching room and perceived clarity was dependent on the instrument type. Since the early part of the time response is more affected in the impression in these types of rooms (Kaplanis et al., 2014), C_{20} results were more associated with the survey results and musicians' expressions than C_{50}. The lack of loudness in the studio room caused reduced support, which can be also seen in the measurement results. On the other hand, the audible resonances related with loudness that occurred in the music teaching room contributed to the perceived support which can be a positive effect of resonances similarly discussed in the study of Halmrast (Halmrast, 2000). With regard to the correlation analysis in both rooms, this study found that the two rooms have similar preferences. However when the resonances become audible, clarity and resonances come into prominence, which is also mentioned as 'resonance and articulation' as a dimension of preference in the study of Wankling (Wankling et al., 2010).

Overall, this study's findings suggest that the influence of reverberation on musicians' impressions in small music rooms was supplemented by spectral modifications at the low frequencies. This supports previous studies and suggests that the perceived sound field can be significantly altered by acoustical distortions in such rooms (Kaplanis et al., 2019). To evaluate resonances and spectral content, Q-Factor and Modal Decay Time analysis was conducted through the measured frequency response and compared with threshold curves. The objective Modal Decay Time values in the studio room exceeded the threshold by a very small amount and the result of the Fisher exact tests showed that the majority of the participants had detected "no resonance" regardless of the instrument type. Hence, the Modal Decay Time threshold curve and Quality Factor threshold values introduced in the literature for reproduction conditions could be suggested to be higher for rehearsal and performance conditions. It was discussed that; low frequency modal resonance would have impacted the perceived sensation of bass, and, the perceived bass does not seem to explain the preference ratings adequately (Kaplanis et al., 2019). Similarly, the correlation coefficient between bassiness and resonances, and the correlation coefficient between bassiness and overall impression were low in both rooms.

The term naturalness, which is mostly associated with reproduction conditions (Kaplanis et al., 2019) can also be used to describe the performance conditions as an indicator of timbre (Dammerud, 2009), and, it was also used to describe the relationship between music stimuli and timbre (Kato et al., 2010). The correlation results showed that an excessive or insufficient level of reverberance, loudness, resonances and bassiness changed the musician's naturalness perception. This result also supports that timbre is not only related with the tonal characteristics of the room, but it also describes the relationship with the loudness of the room as well (Fabiani & Friberg, 2011).

For the investigation of instrument characteristics on the sound field, a classification of instruments is needed for data reduction to search for optimum conditions (Osman, 2005). With the new standard, the instruments are divided according to their sound power generation: for example, quiet, loud, and amplified. Based on the survey results it has been proved that perceived resonances are highly dependent on an instrument's sound power level. This study also attempted to analyze the effect of the tonal range of the instruments, however pitch discrimination is not clear whether limit ranges or fundamental frequency should be considered particularly in the case of the piano example.

Since the study was conducted through a performance-based method, the participant number and the instrument variety were limited. Increasing the number of participants may increase the accuracy of the results.

5. Conclusion

This study aimed to contribute in clarifying the effect of resonances on musicians' perception, and the perceptual differences related to instrument sound level. To analyze the low frequency environment and related distortions, two selected rooms were measured, simulated by the wave-based finite element method, and 24 musicians were interviewed with a performance-based questionnaire. The musicians' data was gathered through face-to-face interviews and analyzed by quantitative analysis.

The recent standard BSI EN ISO 23591:2021 was used for the reverberation time and loudness assessment of the rooms. The reverberation time (T_{mid}) in the music teaching room was within the specified limits, however the participants were not satisfied by the reverberance since resonance related problems changes the musician's reverberance perception. Hence, for the small room assessment the reverberation time is not sufficient to ensure a good level of quality. The results showed that, although reverberation is an easily perceivable and explainable expression in the evaluation of small rooms, the effect of modes occurring at low frequencies in the general impression is one of the main factors that determine the overall preference of musicians. BSI EN ISO 23591:2021 standard specifications were applied in the room assessments in terms of volume and reverberation time and the standard guidelines showed consistency where the results support the significance of the reverberation and loudness. Optimum room dimension, which is specified in the related standard, provides minimization of mode occurrences, however, the mode related specifications need more clarification in terms of the detection of resonances. The Quality Factor and Modal Decay Time threshold values introduced for listening rooms were applied for the assessment of resonances and applicable for resonance assessment for small music rooms, however the limit values towards mid frequency range may be higher for rehearsal conditions. On an instrument basis, it was observed that resonances were detected more in instruments with a high sound power level for individual rehearsal conditions. On the other hand, total attenuation on behalf of resonance solution as applied in the studio room, caused reduced support and low spatial impression.

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References

Acoustics Engineering. (2007). *Measuring Impulse Responses Using Dirac.*

Ayr, U., Martellotta, F., & Rospi, G.

(2017). A Method for the Low Frequency Qualification of Reverberation Test Rooms Using a Validated Finite Element Model. *Applied Acoustics, 116*, 33–42.

Beranek, L. L. (1962). *Music, Acoustics and Architecture.* Wiley; 1st edition.

Bjor, O. H., & Nikolic, I. (2004). *Building and Room Acoustics Measurements With Sine Sweep Technique*. Proceedings Of The Joint Congress Cfa/ Daga'04, Strasbourg, France.

Bolt, R. H. (1947). Normal Frequency Spacing Statistics. *Journal of Acoustical Society of America, 19*, 71–90.

Bonello, O. J. (1981). A New Criterion for the Distributionvof Normal Room Modes. *Journal of the Audio Engineering Society, 29*(9), 597–605.

Bradley, J. S. (2010). *Review of Objective Room Acoustics Measures and Future Needs.* ISRA 2010, Melbourne, Australia.

British Standards Institution. (2008). BS EN ISO 3382-2:2008: *Acoustics—Measurement of room acoustic parameters. Part 2: Reverberation time in ordinary rooms.* London, BSI.

British Standards Institution. (2009). BS EN ISO 3382-1:2009: *Acoustics—Measurement of room acoustic parameters. Part 1: Performance spaces*. London, BSI.

British Standards Institution. (2021). BS EN ISO 23591:2021: *Acoustic quality criteria for music rehearsal rooms and spaces*.

Cipriano, R., Hersberger, R., Hauser, G., Noy, D., & Storyk, J. (2015). *Low Frequency Behavior of Small Rooms.* AES 139rd Convention, New York, NY, USA.

COMSOL Multiphysics. (2018). *Comsol Multiphysics User Guide.*

Cox, T. J., & D'Antonio, P. (2004). *Acoustic Absorbers and Diffusers, Theory, Design and Application.* Taylor & Francis.

Dammerud, J. J. (2009). *Stage Acoustics for Symphony Orchestras in Concert Halls.* University of Bath.

Dance, S. M., & Buuren, G. V. (2013). Effects of Damping on the Low-Frequency Acoustics of Listening Rooms Based on an Analytical Model. *Journal of Sound and Vibration, 332,* 6891–6904.

D'Antonio, P. (2017). *Minimizing Acoustic Distortion in Project Studios*.

Dorrego, F., & Vigeant, M. (2020). The Just Noticeable Difference of Early Decay Time. *The Journal of the Acoustical Society of America, 148*(4). https://doi.org/10.1121/1.5147716

Fabiani, M., & Friberg, A. (2011). Influence of Pitch, Loudness, and Timbre on the Perception of Instrument Dynamics. *The Journal of the Acoustical Society of America, 130*.

Fazenda, B., Stephenson, M., & Goldberg, A. (2015). Perceptual Thresholds for the Effects of Room Modes as a Function of Modal Decay. *Journal of Acoustical Society of America.*

Fazenda, B., & Wankling, M. (2008). *Optimal Modal Spacing and Density for Critical Listening.* Audio Engineering Society, San Francisco, CA, USA.

Gade, A. C. (2015). Classical Musicians' Perception of Room Acoustic Conditions. *Psychomusicology: Music, Mind, and Brain, 25*(3), 232–235.

Gilford, C. (1958). *The Acoustic Design of Talks Studios and Listening Rooms* (No. 1958–28). British Broadcasting Corporation.

Halmrast, T. (2000). Orchestral Timbre: Comb-Filter Coloration from Reflections. *Journal of Sound and Vibration, 232*(1), 53–69.

IBM SPSS Statistics (Version 27.0.). (2020). [For Windows]. IBM Corp.

Kaplanis, N., Bech, S., Jensen, S. H., & Waterschoot, T. van. (2014). *Perception of Reverberation in Small Rooms: A Literature Study.* Audio Engineering Society, Helsinki, Finland.

Kaplanis, N., Bech, S., Lokki, T., & Jensen, S. H. (2019). Perception and Preference of Reverberation in Small Listening Rooms for Multi-Loudspeaker Reproduction. *The Journal of the Acoustical Society of America, 146*(5).

Kato, K., Nagao, T., Yamanaka, T., Kawai, K., & Sakakibara, K.-I. (2010). *Study on Effect of Room Acoustics on Timbral Brightness of Clarinet Tones. Part I: Subjective Evaluation Through a Listening Experiment.* Proceedings of 20th International Congress on Acoustics, Sydney, Australia.

Kleiner, M., Tichy, Jiri. (2014). A*coustics of Small Rooms.* CRC Press.

Kuttruff, H. (2009). *Room Acoustics* (5th ed.). Spon Press.

Lokki, T., Patynen, J., Kuusinen, A., & Tervo, S. (2012). Disentangling Preference Ratings of Concert Hall Acoustics Using Subjective Sensory Profiles. *The Journal of the Acoustical Society of*

America, 132(5), 3148–3161. https://doi.org/10.1121/1.4756826

Løvstad, A. (2003). *Evaluation of Objective Echo Criteria* [Doctor of Philosophy]. Norwegian University.

Mehta, C. R., & Patel, N. R. (2010). *IBM SPSS Exact Tests.* SPSS Inc. 1989, 2010.

Meyer, J. (2009). *Acoustics and Performance of the Music* (5. Edition). Springer.

Noxon, A. (1986). *Room Acoustics and Low Frequency Damping*. 81st AES Convention, Los Angeles, CA, USA.

Olson, H. F. (1967). *Music, Physics and Engineering.* Dover Books.

Osman, R. (2005). *Predicting the Acoustic Quality of Small Music Rooms* [PhD Thesis]. University of Sydney.

Papadakis, N. M. (2017). Application of Finite Element Method for Estimation of Acoustic Parameters. I*n Production Engineering & Management: Vol. Doctorate*. Technical University of Crete.

Park, H., & Jeon, J. Y. (2016). Acoustical Investigation of Ambience Sound for Auditory Environments in Music Performance Spaces. *Building and Environment, 107* (2016), 10–18.

Phillips, S. (2008). Sound Level Measurements in Music Practice Rooms. *Music Performance Research, 2,* 36–47.

Prato, A., Casassa, F., & Schiavi, A. (2016). Reverberation Time Measurements in Non-Diffuse Acoustic Field by the Modal Reverberation Time. A*pplied Acoustics, 110,* 160–169.

Riduan, O. (2010). Designing Small Music Practice Rooms for Sound Quality. *Proceedings of 20th International Congress on Acoustics, ICA 2010*.

Royster, J., Royster, L., & Killion, M. (1991). Sound Exposures and Hearing Thresholds of Symphony Orchestra Musicians. *The Journal of the Acoustical Society of America, 89*(6), 2793–2803. https://doi.org/10.1121/1.400719

Savioja, L., & Svensson, U. P. (2015). Overview of Geometrical Room Acoustic Modeling Techniques. *Journal of Acoustical Society of America, 138*(2), 708–730. https://doi.org/10.1121/1.4926438

Schmalle, H., Noy, D., Feistel, S., Hauser, G., Ahnert, W., & Storyk, J. (2011). *Accurate Acoustic Modeling of Small Rooms.* AES 131st Convention, New York, NY, USA.

Schroeder, M. R., & Kuttruff, K. H. (1962). On Frequency Response Curves in Rooms. Comparison of Experimental, Theoretical, and Monte Carlo Results for the Average Frequency Spacing Between Maxima. *Journal of Acoustical Society of America, 34*(1), 76–80.

Sean, O., Peter, S., James, R., Sharon, S., & Bonneville, M. (1997). The Detection Thresholds of Resonances at Low Frequencies. *Journal of Audio Engineering Society, 45(*3), 116–128.

Shtrepi, L., Astolfi, A., Pelzer, S., Vitale, R., & Rychtáriková, M. (2015). Objective and Perceptual Assessment of the Scattered Sound Field in a Simulated Concert Hall. *Journal of Acoustical Society of America, 138,* 1485–1497. https://doi.org/10.1121/1.4929743

Siltanen, S., Lokki, T., & Savioja, L. (2010). *Rays Or Waves? Understanding the Strengths And Weaknesses of Computational Room Acoustics Modeling Techniques.* Proceedings of the International Symposium on Room Acoustics, Melbourne, Australia.

Stephenson, M. (2012). Assessing the Quality of Low Frequency Audio Reproduction in Critical Listening Spaces. *In School of Computing,Science, & Engineering: Vol. Degree of Doctor of Philosophy.* University of Salford.

Toole, F. E. (2008). *Sound Reproduction: Loudspeakers and Rooms.* Elsevier Ltd.

Vigeant, M. C., Celmer, R. D., Jasinski, C. M., Ahearn, M. J., Schaeffler, M. J., Giacomoni, C. B., Wells, A. P., & Ormsbee, C. I. (2015). The Effects of Different Test Methods on the Just Noticeable Difference of Clarity Index for Music. *Journal of Acoustical Society of America, 138*(1), 476–491.

Vorländer, M. (2013). Computer Simulations in Room Acoustics: Concepts and Uncertainties. *The Journal of the Acoustical Society of America, 133*(1203).

Wankling, M., & Fazenda, B. (2009). *Subjective Validity of Figures of Merit for Room Aspect Ratio Design*. 126th AES Convention, Munich.

Wankling, M., Fazenda, B., & Davies, W. (2010). *Improving the Assessment of Low Frequency Room Acoustics Using Descriptive Analysis.* AES 129th Convention, Audio Engineering Society, San Francisco, CA, USA.