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PRESENTS

Rehearsal room acoustics for the orchestra musician

by M Skålevik

ABSTRACT

The acoustics of the rooms in which orchestra musicians rehearse are very different from the rooms in which orchestras perform. What are the proper acoustics of a good rehearsal room for orchestra musicians? This question calls for a discussion over the conflict between the wish for proper reverberance versus the wish for a proper loudness, in rehearsal rooms that are a lot smaller than the performance room. A rehearsal room with reverberation time equal to the one in the performance space would be way too loud, and a rehearsal room with G or ST that are ideal for the performance space would be way too dry. Current view in our research is that the following topics are strongly related: Stage acoustics, rehearsal room acoustics, performer's perception, and perceived reverberation. The fact that an orchestra musician needs to hear one's own instrument more or less above the other's, may be one of the keys to understanding the mechanisms that has long-term effects on development of sound levels, playing style and noise exposure in an orchestra.

Sound on a musician's ear is in this paper divided into a foreground FG (direct sound from own instrument) and a background BG (direct and reverberant sound from others, and reverberant sound from own instrument). It is concluded that the foreground-to-background balance (FBB=FG-BG) can be sensitive to room acoustical conditions.

BG, when too strong, seems to be able to drive the musician to play louder.

The smaller the ensemble, the more is BG dominated by reverberant sound.

The observation of two rooms having the same T30, but different reverberant levels, and vice versa, would be worth a closer look.

A possible difference in intensiveness of playing during different kinds of sessions – performance, orchestra rehearsal, group rehearsal and individual rehearsal - should be investigated further. While this is relevant to the noise and health concerns, it is expected to be far less relevant to issues of mutual hearing.

The consistency of Dry-Reverb-Balance in approved rooms is surprising but interesting. Its significance and relevance will be investigated, and attempts will be made to describe the perceptual aspect of DRB.

akuTEK navigation:

Home
Papers
Title Index
akuTEK Research
Concert Hall Acoustics

Rehearsal room acoustics for the orchestra musician

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The acoustics of the rooms in which orchestra musicians rehearse are very different from the rooms in which orchestras perform. What are the proper acoustics of a good rehearsal room for orchestra musicians? This question calls for a discussion over the conflict between the wish for proper reverberance versus the wish for a proper loudness, in rehearsal rooms that are a lot smaller than the performance room. A rehearsal room with reverberation time equal to the one in the performance space would be way too loud, and a rehearsal room with G or ST that are ideal for the performance space would be way too dry. Current view in our research is that the following topics are strongly related: Stage acoustics, rehearsal room acoustics, performer's perception, and perceived reverberation. The fact that an orchestra musician needs to hear one's own instrument more or less above the other's, may be one of the keys to understanding the mechanisms that has long-term effects on development of sound levels, playing style and noise exposure in an orchestra. From simulations with models of rooms and ensembles it is concluded that even where reverberant sound has little direct effect on the sound pressure levels at the musician's ear, it could indeed have an important indirect effect by driving the musician to play louder.

1 Introduction

The acoustics of the rooms in which orchestra musicians rehearse are very different from the rooms in which orchestras perform. Moreover, rooms for different kind of rehearsal differ very much from one another. What are the proper acoustics of good rehearsal rooms for orchestra musicians? Conventionally, there have been attempts to extrapolate from criteria established for large concert halls. However, this inevitably leads to a conflict between the wish for proper reverberance versus the wish for a proper loudness, in rehearsal rooms that are a little smaller, or even a lot smaller, than the performance room. A rehearsal room with reverberation time equal to the one in the performance space would be way too loud, and a rehearsal room with G or ST that are ideal for the performance space would be way too dry. Table 1 presents combinations of typical use, number of musicians and values for volume, reverberation time T30 and room gain G_r (in musicians' area, subscript r denotes reverberant sound only), all values satisfying the new Norwegian Standard NS8178, [1].

Table 1 Examples of very different music rooms with combinations of intended use, number of musicians, volume, reverb time T and reverberant gain G_r , all satisfying the new Norwegian Standard NS8178

Room and use	# musicians	Volume (V)	T	G_r
Small rehearsal room for individual practice	1	40 m^3	0.4s	25 dB
Medium size rehearsal room for group rehearsals, e.g. 1st violin	15	700 m^3	0.8s	18 dB
Large rehearsal room for full orchestra rehearsals	80	5600 m^3	1.1s	8 dB
Concert hall	80	18000 m^3	2.1s	5 dB

As can be seen from the table, there is a large variation in all values, even if all the four different rooms are considered very good for their use. When two of the three parameters V, T and G_r are given, the third can be predicted by Barron Revised Theory (BRT), if the sound field is sufficiently diffuse. By empirical approach, it has been possible to establish recommended combinations of volume and reverberation times for each category of use, e.g. performance or individual, group or orchestra rehearsal. However, it still remains to establish a perception based criterion for "musicians' acoustical environment" from which proper combinations of V, T and G_r can be derived. E.g. for a given room, V is given. Then G_r would depend directly from a choice of T and vice versa.

This paper aims for a continued pursuit for the aforementioned unknown parameter, as a contribution to the structured session "Acoustics of buildings and rooms for music rehearsal and performance" at BNAM2014, Tallin, 2014.

2 Previous work

2.1 Reverberation time and accuracy of musical taste

In the literature of Architectural Acoustics, there are many suggestions for suitable combinations of reverberation time and volume in rooms for specific types of music. Based on systematic experiments with 5 rooms varying in volume from 78 to 210m^3, Sabine [2] arrived at a preferred reverberation time for piano music equal to 1.08 s, with a mean deviation of 0.05s from this mean value (1902). Sabine reported the result in a chapter about accuracy of musical taste. In similar manner, 2.0s in concert halls for symphony orchestras could be another example of musical taste. However, it is crucial to keep in mind that such results have external validity only to similar cases.

2.2 Scaling V and T

One early 1900's example [3] of "scaling" reverb time with room size was the idea to maintain a constant ratio between the reverberant radius and the linear dimensions of the room, leading to T proportional to $V^{1/3}$ (Watson, 1923). However, it is not practical to scale music rooms without changing the geometrical ratios. Besides, if trying to downscale from 2.0s of the big concert hall, with respect to $V^{1/3}$ regardless of geometry, the small music room would be too dry. Several decades later, a weaker dependency, using $V^{1/7}$ was suggested [6], based on the principle of keeping increments dT and dE equal to the just noticeable differences of decay time and energy level, respectively (Cremer & Müller 1982). However, this has been criticised for leading to small music rooms being overly reverberant and loud. Nijs et al [7] presented a wide discussion of approaches in order to maintain consistency while trying to find more proper combinations of V, T and G (2005) in smaller music rooms.

An even more advanced development in this tradition can be found in the aforementioned new music room standard, NS8178: It has one set of V-T curves for each of the three music types, reinforced music, powerful acoustical music, and less powerful acoustical music. Moreover, its Annex provides a method to predict sound pressure levels at forte for a given ensemble and a given V-T combination. It remains to settle which forte levels actually are the preferred ones, whether the preferred forte level from a flute is the same as the preferred forte level from a trombone, and so on. Once the statistics for such preferred values are established, one would have reached a perceptually based criterion that links a V-T combination to a certain G value. By today this is a missing link.

2.3 Temporal features vs Loudness features

When it comes to musicians' acoustical environment, the literature leaves more focus on the features of sound levels than on decay times. E.g., "noise exposure levels", "support level", "hearing others with proper loudness", "masking levels" and even "reverberation loudness", tends to be more emphasised than reverberation time and Reverberance. This is demonstrated by the vast number of suggested energy parameters. In addition to the encouragement from the room acoustics segment of "Musicians' Acoustics", research is also motivated by the concerns of Workplace Health. The latter is exemplified below.

2.4 Status

No single parameter suggested in literature is yet proven meaningful as a criterion throughout a great variation in room size and use. In 2012, two authors [2][3] independently arrived at the parameter A/N, and its equivalent V/(T·N), as a parameter for controlling loudness in ensembles. However, the suggested criteria values would only be valid as long as the sound power statistics of a group of N musicians were similar, and it remains to establish criteria values for other ensembles than symphony orchestras.

3 New data, new ideas

At this point, the field of Room Acoustics for musicians can benefit from a substantial amount of useful data from a survey in The Queensland Orchestra (TQO), motivated by Workplace Health, i.e. concerns of hearing damage related to noise exposure in musicians [6] (O'Brian et al 2008). Over a period of three full years ranging from 2004 to 2007, a total of 1609 samples of exposure levels at musicians' ears were acquired during orchestra rehearsals and performances in the rehearsal studio, orchestra pit and in the concert hall of the Queensland Performing Arts Centre (QPAC). Samples were in quantities of L_{Aeq} and $L_{C,peak}$, and well distributed over all instruments of the orchestra. The measurement time of the samples is not known, but is assumed to be equal to the duration of one session, typically a 1.5 hour rehearsal or 2-3 hours including breaks for performances in the pit or in the concert hall. In the paper, sample averages together with maximum and minimum for each instrument/part were presented.

A comprehensive literature study with references [7]-[21] was given.

3.1 Foreground and Background

In addition to the amount of data published by O'Brien et al, their paper establishes two important facts:

a) the sound level at a musician's ear is in general determined by the musician's own instrument

b) a musician must hear their own instrument above all others in order to play, after all

This author arrived at the same conclusions as expressed in a) and b) in a report from a noise survey in the Oslo Philharmonic Orchestra (OFO) in 2013[22].

The simple facts stated in a) and b) above have quite far-reaching implications, at least relevant to the driving mechanism of sound levels in ensembles. However, it is crucial to keep the logics straight. If b) is not taken into account, a) alone would appear to imply that room acoustics and direct sound from colleagues does not affect the sound level at a musician's ear. On the contrary, b) imply that direct and reverberant sound from the sum of all instruments, hereafter referred to as the Background Level (BGL), is capable of forcing the individual musician to play louder than the musical intention would imply.

We shall refer to the sound level from the musician's own instrument as the Foreground Level (FGL). The combination of a) and b) implies an indirect impact from BGL to FGL, and a feedback loop because someone's FGL is another one's BGL, which again would affect other's FGL, and so on. It has similarities with the Lombard effect, the observation of speech levels being raised in noisy environments, the feedback loop arising from the fact that someone's speech is another one's noise.

- FGL Foreground Level, level at own ear from direct sound of own instrument, determined by inherent instrument properties like directivity and source-to-ear distance
- BGL Background Level, level at own ear from direct and reverberant sound of other instruments and reverberant sound of own instrument, determined by neighbouring instruments (orchestra layout) and reverberant sound from the whole orchestra, the neighbour-radius being yet to establish
- FBB Foreground-Background Balance FGL-BGL

It is assumed that the balance between foreground and background, FBB=FGL-BGL, statistically should be above a critical value in order to avoid unintended changes in playing style, e.g. some musical variant of the Lombard Effect. On the other hand, it is assumed that the musician would like to hear as much as possible of the orchestra and of the reverberant sound as long as the FGL-BGL balance is uncompromised. Thus, we expect FGL-BGL to have an optimum value, i.e. too much and to little would be equally unwanted. Further, if FGL-BGL is sufficiently sensitive to reverberant sound, we would have a perceptually based criterion for the level of reverberant sound. If it on the contrary is very little sensitive to reverberant sound, i.e. the reverberant part of BGL is of insignificant size, it would be questioned whether reflected sound can have any significance to musicians at all. A study of the FGL-BGL balance seems to be worthwhile.

A new computer model study was carried out on the basis of the results above, using Odeon 12, as will be described below. This model would be different from the one in a previously published study [26][27], which showed how different parts of the orchestra would contribute differently to the sound levels in some points in the orchestra, in different time intervals (direct, early, late and total).

4 An orchestra model in Odeon

A model of an orchestra was built in Odeon, tuned to match the Queensland data referred to above, with the purpose to study the foreground-background balance, FBB=FGL-BGL, as motivated for above.

The orchestra was divided into 4 sections, strings, woodwinds, brass and percussion, and a single string instrument musician. Each section and the single musician was modelled as surface sources having internal power balance equal to the one calculated from the average of equivalent a-weighted sound power levels, a total of 401 samples from the concert hall in QPAC. Calculated sound power levels per section, normalized to the total sound power of all sections, are presented in Table 2. The "High" and "Low" columns is shown in order to get an idea of how the internal power balance can be different in loud and quiet sessions respectively. The power balance of the sections in the model was tuned to be equal to the values in the "Average" column, namely the average of 401 equivalent levels in Queensland. Related to this normalization, the power level of the single string player is -21dB in the average case. At forte play, the total power level is calculated to be 8dB higher than at the average equivalent level, being 114dB and 106dBA, respectively. Note that brass is much more dominant at tutti forte than in average session periods. While strings, woodwind and percussion are 5dB more powerful than average session period, brass is 13dB more powerful at tutti forte. Forte power levels are from [1], with references to [25] and [27].

In relevance to dynamics, it is worth mentioning that LAeq levels in 60 second periods, near musicians ear, during rehearsal and concert session, varied with a standard deviation of s=7dB as a mean over different instruments [24]. Smallest variation was found in Oboe/French Horn section (s=5dB) and biggest variation in Horn section (s=9dB). During each 60-second period, standard deviation over the orchestra was as high as 7dB in some periods and as low as 3dB in some periods, with a mean value of 4dB. For more than 12% of these periods, the maximum difference between two instruments was 20dB or more.

Table 2 A-weighted sound power levels (LwA) per section, normalized to the total sound power of all sections, details given in text

Section	Musicians #	L_{wAeq} Low (dB)	**L_{wAeq} Average (dB)**	L_{wAeq} High (dB)	$L_{wA,Tutti}$ Forte (dB)
Strings	50	-3	**-4**	-4	-8
Woodwind	12	-7	**-7**	-8	-10
Brass	12	-6	**-6**	-6	-2
Percussion	6	-11	**-8**	-6	-11
Total	80	0	**0**	0	0

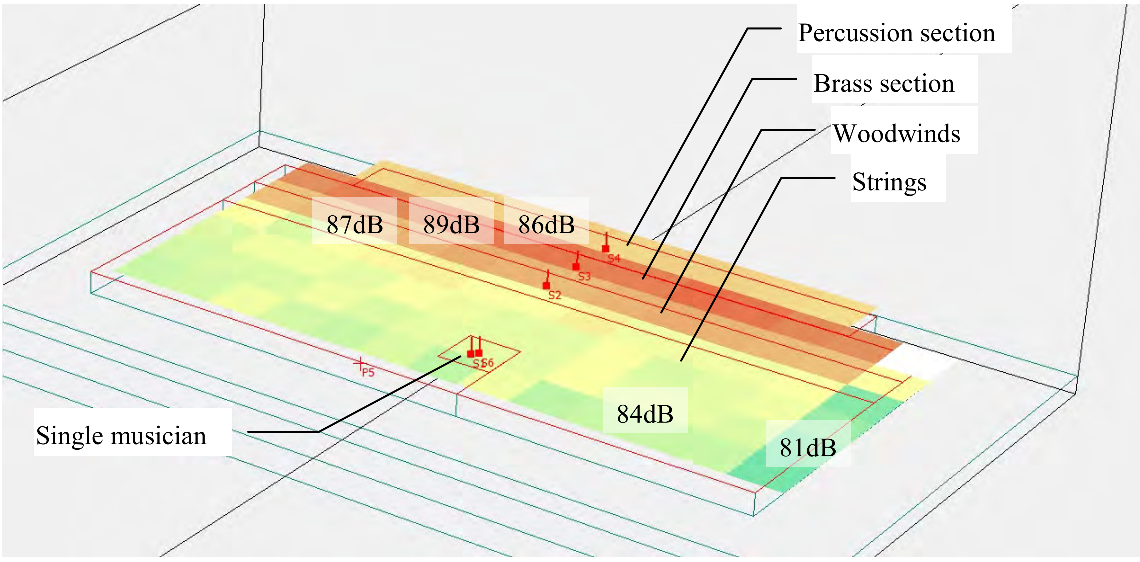

Figure 1. The symphony orchestra modelled in Odeon 12 for the purpose of this study. Examples of long-term averages of LAeq (dB) in a 18000m3 concert hall. Note the weaker levels at the edge of the string section.

An illustration of the orchestra model and examples of LAeq levels are given in Figure 1. In the model, the sound power of each section is evenly distributed over the area that each section occupies. This is according to the assumption that over a long period of time (the data was acquired over a three year period), internal instruments positions would vary sufficiently to cancel those local hot and cold spots that would be seen in measurements from a single session.

In order to see how the foreground and background sound levels behave when a musician moves between different rooms and different rehearsal and performance sessions during daily life as an orchestra musician, a number of models of different room and ensemble configurations were made. It was chosen to restrict the study to the case of 1^{st} violin section member only, and to four rooms. The four rooms, number of musicians, and room volume was as described by Table 1, and illustrated in Figure 2. Different amount and distribution of absorption was tested, and thus the T and G_r in each room would vary from the example value in the table.

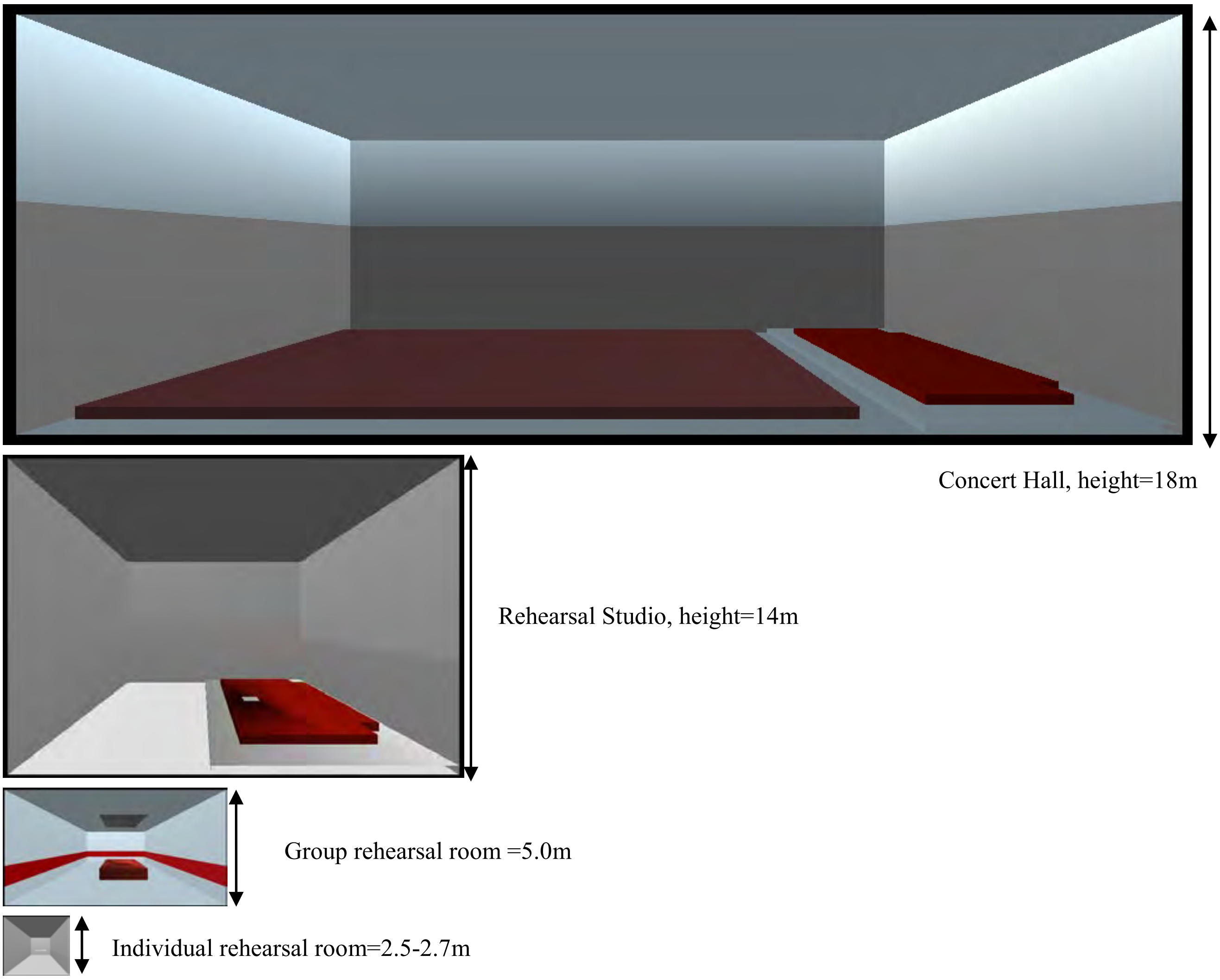

Figure 2. The four music room room models in Odeon

5 Results and comments

Examples of results from simulations are presented in Table 3. All four rooms have been tested in different versions, trying to see the effect of varying amount and distribution of absorption in each room, as can be seen from the T30-rows. In the concert halls, the rehearsal studios and the group rehearsal rooms, the equivalent A-weighted sound pressure level, LAeq, from all musicians, are all within the interval of 83.4 to 85.1dB. In the individual rehearsal rooms, LAeq varies within the interval of 82.4 to 83.5. The lower levels of the individual rooms can be explained by the absence of other musicians, and the fact that the reverberant level from own instrument is too weak to fully compensate for this absence, even in rather live practice rooms.

In individual rehearsal rooms, the background BG is determined by the reverberant sound from own instrument alone. Thus the foreground to background balance FBB=FG-BG is also lower than when other musicians are present.

The smaller the ensemble, the more sensitive to reverberant sound is the FBB. If the FBB is to vary as little as possible as the musician moves from one rehearsal situation to another, the reverberant level should be tuned to satisfy this criterion.

The variation of BG dominates the foreground to background balance FBB=FG-BG.

Note that those concert halls, rehearsal studios and group rehearsal rooms that have T30 values (bold) inside recommended limits, all have very consistent FBB levels, with values in the narrow region of FG-BG=2.0-2.2 (bold). In contrast the FBB in individual practice rooms vary within FG-BG=5.0-7.6 in the three rooms having a recommended T30 equal to 0.4s.

One unexpected, but very interesting result, is seen in the Dry-Reverb-Balance DRB (all instruments). While the total variation of DRB is from 3 to 13dB, all rooms with recommended T30-values ("OK" or "x") have consistent values in the range of 6-7dB. The perceptive aspect of DRB is yet to be described.

Note that there are several examples of two rooms having the same T30, but different reverberant levels, and vice versa.

Table 3 Extract of results from simulations in the Odeon models. "Dry" means without reverberant sound. "KM" indicates a point measurement near the konzertmeister / conductor position. "-" means "not applicable" or a value too weak to be computed (typical in the row reverberant level, self). "NS8178 T30(V) highlimit/lowlimit" refers to recommended T30 limits, as a function of volume (V), given in the standard NS8178. "i8178" means an individual rehearsal room that satisfies the height and volume requirements of NS8178. "LE" and "DE" means in the live end and the dead end of a room with such absorption distribution.

Room type	CONCERT HALL			REHEARSAL STUDIO					GROUP REHEARSAL			INDIVIDUAL REHEARSAL ROOMS						
Room ID	CH	CHb	CHc	RHa	RHb	RHc	RHd	RHe	g15c	g15d	g15e	i2a	i2c	i2d	i2e	i8178	i8178LE	i8178DE
L	50	50	50	20	20	20	20	20	14	14	14	2,9	2,9	2,9	2,9	3	3	3
B	20	20	20	20	20	20	20	20	9,6	9,6	9,6	3,8	3,8	3,8	3,8	5	5	5
H	18	18	18	14	14	14	14	14	5	5	5	2,5	2,5	2,5	2,5	2,7	2,7	2,7
N	80	80	80	80	80	80	80	80	15	15	15	1	1	1	1	1	1	1
V	18000	18000	17800	5600	5600	5600	5600	5600	691	691	691	28	28	28	28	41	41	41
T30 KM (occ)	2,1	1,6	2,2	1,3	1,1	1,2	1,1	2,3	0,9	1,6	0,8	0,2	0,4	0,4	0,5	0,4	0,7	0,7
T30 glob (occ)	2,2	1,5	2,2	-	-	1,3	1,1	2,4	0,9	1,5	0,6	-	0,4	0,4	0,5	0,4	0,7	0,7
T30 glob (unoccupied)	2,5	*1,3*	*2,7*	-	-	1,8	1,4	*3,7*	1,3	*2,7*	*0,6*	-	-	-	-	-	-	-
Approved (x=NS8178)	**OK**	-	***OK***	-	-	**x**	**x**	-	**x**	-	-	-	-	-	-	**x**	-	-
LAeq (all)	**84,1**	**83,9**	**84,1**	**84,4**	**83,9**	**84,1**	**84,1**	**85,1**	**84,1**	**85,0**	**83,3**	**82,4**	**82,7**	**83,2**	**83,5**	**83,0**	**83,8**	**83,2**
LAeq (self)	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,1	82,2	82,0	82,4	82,7	83,2	83,5	83,0	83,8	83,2
LAeq (others)	80,0	79,5	79,8	80,5	79,4	79,9	79,8	82,2	79,8	81,8	77,3	-	-	-	-	-	-	-
dryself	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0
dryothers	77,4	77,4	77,4	77,4	77,4	77,4	77,4	77,4	76,5	76,5	76,5	-	-	-	-	-	-	-
dry all	83,3	83,3	83,3	83,3	83,3	83,3	83,3	83,3	83,1	83,1	83,1	82,0	82,0	82,0	82,0	82,0	82,0	82,0
reverberant level all	76,3	75,0	76,3	77,9	75,0	76,3	76,3	80,4	77,2	80,5	69,8	71,8	74,4	77,0	78,1	76,1	79,1	77,0
reverberant level, others	76,5	75,3	76,0	77,5	75,0	76,3	76,0	80,4	77,0	80,2	69,5	-	-	-	-	-	-	-
reverberant level, self	-	-	-	-	-	-	-	-	65,6	68,7	-	71,8	74,4	77,0	78,1	76,1	79,1	77,0
FG	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0	82,0
BG	79,9	79,3	79,9	80,6	79,3	79,9	79,9	82,1	79,9	81,9	77,3	71,8	74,4	77,0	78,1	76,1	79,1	77,0
FG-BG	**2,0**	2,5	**2,2**	1,5	2,6	**2,1**	**2,2**	-0,2	**2,2**	0,2	4,7	10,2	7,6	5,0	3,8	**5,9**	2,9	5,0
Dry-Reverb (all) Balance	**7**	8	**7**	5	8	**7**	**7**	3	**6**	3	13	10	8	5	4	**6**	3	5
NS8178 T30(V) highlimit	-	-	-	1,8	1,8	1,8	1,8	1,8	1,2	1,2	1,2	0,4	0,4	0,4	0,4	0,5	0,5	0,5
NS8178 T30(V) lowlimit	-	-	-	1,2	1,2	1,2	1,2	1,2	0,8	0,8	0,8	0,3	0,3	0,3	0,3	0,3	0,3	0,3
NS8178 medium T30	2,0	2,0	2,0	1,5	1,5	1,5	1,5	1,5	1,0	1,0	1,0	0,3	0,3	0,3	0,3	0,4	0,4	0,4
10lg(T.NS) KM	0,2	-1,0	0,4	-0,5	-1,2	-0,9	-1,2	2,0	-0,5	2,0	-1,0	-2,1	1,0	1,0	1,9	0,0	2,4	2,4
ST early (unocc)	*-20*	*-21*	*-18*			*-19*	*-18*	*-16*	*-7*	*-6*	*-14*					*-1*		
ST late (unocc)	*-14*	*-17*	*-16*			*-14*	*-16*	*-9*	*-8*	*-3*	*-21*					*-11*		
ST total (unocc)	*-13*	*-15*	*-14*			*-13*	*-14*	*-8*	*-5*	*-1*	*-13*					*-1*		
T30 (unocc)	*2,5*	*1,3*	*2,7*			*1,8*	*1,4*	*3,7*	*1,3*	*2,7*	*0,6*					*0,5*		
Stbal	*-6*	*-4*	*-2*			*-5*	*-2*	*-7*	*0*	*-3*	*7*					*9*		
Sttot+10lgN	*5*	*2*	*3*			*5*	*3*	*10*	*4*	*9*	*-9*					*-11*		
Sttot+10lgN	*6*	*4*	*5*			*6*	*5*	*11*	*7*	*11*	*-1*					*-1*		
T, all	2,2	1,5	2,2	1,4	1,4	1,4	1,1	2,3	0,9	1,5	0,6							
T, others	2,3	1,5	2,3	1,5	1,6	1,6	1,1	2,3	0,9	1,5	0,6							
G, all	3,1	2,9	3,1	3,4	2,9	3,1	3,1	4,1	3,1	4	2,3							
G, others	-1	-1,5	-1,2	-0,5	-1,6	-1,1	-1,2	1,2	-1,2	0,8	-3,7							
EDT, all	1,5	1,2	1,3	1,5	1	1,5	1,3	2,2	0,6	1,3	0							
EDT, others	1,6	1,3	2,1	1,3	1,3	1,3	1,2	2,3	0,9	1,4	0,3							
C, all	8,2	10	8,8	6,4	8,9	7,7	8,4	3,7	10,9	6,6	22,2							
C, others	2,9	4,7	3,7	1	3,2	2,2	3	-1,5	6,3	2,6	16,5							

In extremely live rehearsal studios and group rehearsal rooms, the reverberant sound directly contributes to sound pressure levels that are higher than those experienced in the concert hall, as can be seen in rooms RHe and g15d. In these examples we also see FBB's that are 2dB lower than on the concert hall stage and in the well-tuned rehearsal rooms.

It should be noted that the models in this study assume the average emitted power from musicians is equal in all sessions - orchestral performance, orchestra rehearsal, group rehearsals or individual rehearsal. Since group and individual rehearsals have the possibility to skip the silent parts, the sessions could be more intensive. On the other hand, there are subjective and objective indications of more powerful playing during orchestra performance than orchestra rehearsal.

6 Conclusion and Further work

Sound on a musician's ear is in this paper divided into a foreground FG (direct sound from own instrument) and a background BG (direct and reverberant sound from others, and reverberant sound from own instrument). It is concluded that the foreground-to-background balance (FBB=FG-BG) can be sensitive to room acoustical conditions.

BG, when too strong, seems to be able to drive the musician to play louder.

The smaller the ensemble, the more is BG dominated by reverberant sound.

In further work, the present study should be extended to include other instruments and more spectral data than the just mid-frequencies. In individual rehearsal rooms it remains to settle the proper level of the reverberant sound, since the observed variation is big among rooms that have the recommended T30 according to NS8178. Also, the delicate hearing balance and masking effects discussed below should be pursued. In addition to more simulations, measurements and analytical methods will be included in the research. Since the orchestra model in our study was a plane surface with no obstacles, one should try to analyse what the effect of such obstacles would have on BG in the bigger ensembles.

The observation of two rooms having the same T30, but different reverberant levels, and vice versa, would be worth a closer look.

A possible difference in intensiveness of playing during different kinds of sessions – performance, orchestra rehearsal, group rehearsal and individual rehearsal - should be investigated further. While this is relevant to the noise and health concerns, it is expected to be far less relevant to issues of mutual hearing.

It must be distinguished between the direct effect and the indirect effect of room response. While the direct effect can cause a musician to play stronger when the room response is weak and vice versa, i.e. a negative feedback loop, the indirect effect is a positive feedback loop: Stronger reverberant sound from an ensemble can drive the individual musician of the ensemble to play louder, trying to improve an insufficient FBB.

The consistency of Dry-Reverb-Balance in approved rooms is surprising but interesting. Its significance and relevance will be investigated, and attempts will be made to describe the perceptual aspect of DRB.

7 Discussion

For music performance spaces with properties different from the selection of concert halls from which the 2.0s criterion was found, the criterion would not be valid in general. The same goes for Sabine's aforementioned music rooms, which all were 4 meters high, and which tests were restricted to particular examples of piano music, all performed by the same Mr. Proctor, and judged by prominent gentlemen at New England Conservatory of Music. While there is no reason to doubt that the reported preference is valid under the given conditions, one cannot extend its validity to any room heights, any room volumes, and any kind of music played by any musician for any audience. On the other hand, Sabine's point – that this is an example of how reverberation time (in combination with volume and other conditions, we might add), is subject to musical taste which can be of remarkable accuracy, is indeed valid. The 2.0 s reverb time in concert halls is another example of accuracy in musical taste, but not in a $30m^3$ rehearsal room. Musical taste is sensitive to other features than the decay of reverberant sound. Loudness is one, and Sabine emphasised this feature for its prominent significance. In the case of large concert halls, at least in the rear half of the auditorium, a sufficiently long reverberation time would be necessary in order to achieve powerful sound, regardless of whether or not it is necessary for proper reverberance.

Together, the statements a) and b) in 3.1 imply that reverberant sound does have an indirect influence on musicians, but not a direct one. The lack of direct influence could explain why orchestras seldom respond consistently, i.e. with statistical significance, to sudden changes in acoustical environment, like in experiments with variable acoustics. Moreover, the indirect influence could explain reported changes in playing style in orchestras having been exposed to a change in acoustics over a sufficient number of days or weeks. E.g. a resident orchestra struggling for years with the acoustics in their concert hall have been observed to play differently in their first concert after coming home from a long tour [30]. Another example is the resident orchestra compensating for a long-term lack of acoustical response in their concert hall, adopting a more forced style of playing that may not be noticed at home, but becomes evident when on tour in more live concert halls. The inertia of the indirect influence mentioned above makes it hard for a big orchestra to adapt to such a sudden change in live-ness in the acoustical environment. Actually, the dominant part of this environment is often the direct sound from other instruments, and this part can only be changed slowly (if not instructed by a conductor, and if not the orchestra is unusually well trained to make such adaptions).

The Foreground-Background Balance, FBB=FGL-BGL, can be considered analogue to a signal-to-noise ratio level, in the sense that in the need of a musician to hear one's own instrument sufficiently above the others', the sound of own instrument is the signal and the sound of others' is noise. However, in the next moment, a musician needs to hear others, thus turning the signal-noise analogue upside down. When trying to hear one's own instrument, it would be good if FBB was high. But in the next moment, when trying to obtain information from the background, it would be good if FBB was low. If the FBB is not optimal, it may require too much processing for the brain to unmask the signal of interest. From this conflict it must be expected that the FBB has a very delicate optimum.

A more precise way to look at the orchestra musician's hearing challenges could be to define the three important signal sources

- Own instrument
- Other instruments
- Room response

The priority order of the signal sources may change from one moment to another, but in most events it would be in the above order. Whenever one of these sources is of main interest, the others become noise, or maskers. The critical levels of the maskers are expected to be different for different sources, i.e. the signals of higher priority would require better signal-to-maskers ratio than those of lower priority. E.g. Own instrument would require a positive signal to masker ratio level, while Room Response could be more than 10-20dB weaker than the sum of Own and Other, and still be heard.

It is important to distinguish between the indirect effect of room acoustical response upon the individual musician, as described in this paper, and its direct effect upon the individual musician. The direct effect has been observed in different cases of music playing, i.e. the adaptation by compensating for too strong feedback from the room [31] or from loudspeakers, e.g. a monitor loudspeaker, by playing softer, and compensating for weak feedback by playing stronger. However, if the individual musician finds the sound of others, i.e. the Background level BGL, to be too strong, it would not help to play softer. Actually, the opposite would be the case – it would help for a while to play louder, but only until others do the same. In this indirect effect, "others" are introduced in the chain of the feedback loop Self – Room – Others – Self. In this case, a reduced room response could help. "Others" will provide inertia in the loop and thus slow down the escalating effect. Another inertial effect would be the self-discipline of musicians, their experience and their ability to play with a weak FBB.

The aforementioned direct effect from room response is more likely to occur in solo play and other cases when the musician clearly perceives the room response, e.g. during individual rehearsal. Even if the strongest cases of room response are found in rehearsal rooms, the differences in room gain are not completely compensated by musicians' differences in output power. Reports exist for trumpet rehearsal rooms [32], and for small wind and brass rehearsal rooms [33]. It has been suggested that trained musicians by experience judge their dynamics and output power from the direct sound, not from room response, thus counteracting any adaption to room acoustics, i.e. the direct effect.

For the direct effect to occur when playing in or with an ensemble, the room response from own instrument would have to be strong enough, and late enough, to be perceived above masking level due to sound from co-players.

An example of the complexity of these issues is the significance of frequency spectrum in halls and musical instruments. In case of a concert hall having too weak mid-low frequency response but strong brilliance, driving the musicians to play harder, i.e. a direct effect, the sound sources become more high frequency dominated. Due to the brilliance of the hall, the BG would increase more than does the FG, thus reducing the FBB. Hence the indirect effect would set in, driving musicians to play even harder. The opposite case is the warm hall, having rich low-mid frequency response. If the direct effect sets in, it would tend to make the musicians play less strong, since the feedback from the room would be more dominant in the BG the softer they play. The stronger they play in this warm hall, the less would the room response play a role and the higher would the FBB be. Thus in a warm hall, the indirect effect, i.e. the positive feedback, is counteracted. In contrast, the brilliant hall has an inherent instability that would drive the musicians into ever decreasing hearing conditions, and playing ever harder than the musical intention would imply. These examples bring in new arguments in the discussion over warmth vs brilliance in concert halls, and new insights for the understanding of the interdependence between room acoustics, podium acoustics, ensemble acoustics, mutual hearing and the sound quality of the music that eventually reaches the listener's ears.

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