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Rooms for music – Acoustical needs and requirements

by J H Rindel

ABSTRACT

A new Norwegian standard NS 8178 has been established with the aim to improve the facilities used for music; especially in relation to music teaching and rehearsing of non-professional ensembles it is found that the rooms are often very unsatisfactory in terms of the acoustics. The standard specifies recommended dimensions and reverberation times for various types of music and various sizes of music groups. Three types of music are considered; amplified music, powerful acoustic music, and weak acoustic music. The recommended reverberation times as a function of the room volume have been derived by considering the average strength G of the room and the typical sound power generated by musical instruments when played at forte. For rehearsal rooms, a somewhat shorter reverberation time is recommended compared to performance rooms of the same size.

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Rooms for music – Acoustical needs and requirements

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A new Norwegian standard NS 8178 has been established with the aim to improve the facilities used for music; especially in relation to music teaching and rehearsing of non-professional ensembles it is found that the rooms are often very unsatisfactory in terms of the acoustics. The standard specifies recommended dimensions and reverberation times for various types of music and various sizes of music groups. Three types of music are considered; amplified music, powerful acoustic music, and weak acoustic music. The recommended reverberation times as a function of the room volume have been derived by considering the average strength G of the room and the typical sound power generated by musical instruments when played at forte. For rehearsal rooms, a somewhat shorter reverberation time is recommended compared to performance rooms of the same size.

1 Introduction

The acoustics of a room are of decisive importance for how the interaction between the room and a musical instrument is working. In recent years there has been a growing understanding of the importance of dealing actively with music for the general development of children. Researchers from North-western University have found that the neural connections made during musical training also prime the brain for other aspects of human communication [1]. They also report that children who are musically trained show stronger neural activation to pitch changes in speech and have a better vocabulary and reading ability than children who did not receive music training.

In Norway it is a long tradition that a school should have a music band that will perform on various occasions, not the least on the National day, 17th May. However, especially in relation to music teaching and rehearsing of non-professional ensembles, it is found that the rooms are often very unsatisfactory in terms of the acoustics. While there are well-established requirements for rooms devoted to various kinds of sport, the requirements for music rooms have been very weak, or fully missing. This is the background for the new Norwegian standard NS 8178 [2].

The standard contains detailed requirements for three types of music; amplified music, powerful acoustic music, and weak acoustic music. This paper deals with acoustic music, only, because the sound level created depends on many factors related to both the instruments and the room, whereas for amplified music the level is simply adjusted by the power amplifier.

2 Sound levels and dynamic range in music

Music played in a room with musical instruments without electrical amplification create an average sound level depending on the following conditions:

- The musical instrument, type and number of instruments
- How the instrument is played, especially the dynamic expression
- The volume of the room
- The reverberation time in the room

Musical instruments can be string instruments (bowed or plugged), woodwind, brass instruments, percussion, or keyboard instruments. Song without amplification is also included, although strictly speaking not an instrument. The instruments can be single or in groups; small chamber music groups, music bands, orchestras, chorus etc.

Most musical instruments can be played with different sound power, from quiet to loud. In musical terminology, the dynamic levels are denoted ***piano*** (quiet) or ***forte*** (loud). A more complete list of musical dynamic expressions is shown in Table 1.

Table 1. Dynamical notations in music with explanation and approximate equivalent sound pressure levels.

Symbol	Meaning	Description	Approximate SPL
ppp	*piano pianissimo*	extremely quiet	45-50 dB
pp	*pianissimo*	very quiet	55-60 dB
p	*piano*	quiet	65-70 dB
mf	*mezzo forte*	medium loud	75-80 dB
f	*forte*	loud	85-90 dB
ff	*fortissimo*	very loud	95-100 dB
fff	*forte fortissimo*	extremely loud	105-110 dB

The approximate SPL that corresponds to the different dynamic levels in music are also given in Table 1. These levels can be seen as typical in a good concert hall. The dynamic range can be very large, up to around 60 dB is possible in a symphony orchestra. However, with single instruments the typical dynamic range is somewhat smaller, around 25 to 30 dB, a little less for e.g. flute and saxophone, a little more for e.g. violin and clarinet.

For the evaluation of the loudness in concert halls Wu et al. [3] have looked at the mean ***forte*** sound pressure level of ***tutti***-sound, and have suggested the optimum range to be 85 – 91 dB. This agrees well with Meyer [4] who has found that the sensation of spaciousness requires a level around 85 – 92 dB, and 90 dB being the optimum. In the new Norwegian standard the basis for the acoustic evaluation of a music room is $L_p(f)$ in the range 85 – 90 dB, and this is applied to rehearsal rooms as well as performance spaces.

3 The sound power level at *forte* for musical instruments

The sound power from musical instruments has been studied in great detail by Meyer [5, 6]. I order to handle the difficulties related to the various ways of playing and the great dynamic range, Meyer assumed four equal steps from ***pp*** to ***ff***, and thus he calculated the sound power level at ***forte***:

$$L_W(f) = L_W(ff) - \frac{D}{4} \text{ (dB)} \tag{1}$$

where $L_W(ff)$ is the sound power level at fortissimo and D is the dynamic range:

$$D = L_W(ff) - L_W(pp) \text{ (dB)} \tag{2}$$

and $L_W(pp)$ is the sound power level at pianissimo.

The total sound power level at ***forte*** for a number n_i of instruments type i, is then estimated from:

$$L_W = 90 + 10 \log \sum_i n_i\, k_i \text{ (dB)} \tag{3}$$

where k_i is the sound power factor of instrument type i:

$$k_i = 10^{(L_{W,i}(f)-90)/10} \text{ (dB)} \tag{4}$$

Burghauser & Spelda [7] have published very detailed data of sound emission from a very large number of musical instruments, measured in the 1960'ies in Czechoslovakia. Their data were also applied by Meyer [4] for the most common instruments in the classical symphony orchestra. For the purpose of the Norwegian standard NS 8178 the list of instruments has been extended to include 41 instruments, including examples of singers.

The method of converting the measured data to the sound power level at ***forte*** is described in [5]. There are several difficulties to deal with in the interpretation of the original data.

- The measurements were made in a radio studio (***V*** = 1460 m^3 and ***T*** = 1.45 s). The distance to the microphone varied for different groups of instruments, so for some of the instruments the direct sound may influence the measurements.
- The instruments were played at three dynamic levels; ***pp***, ***mf*** and ***ff***. However, the low levels were measured with the A-weighting filter, the medium levels with the B-weighting filter, and the high levels with the C-weighting filter. This means that the measurement results especially from the instruments playing in the low frequency range need to be adjusted in order to compensate for the different frequency weightings.

For these reasons plus the fact that instruments are different and individual musicians play differently, the data that has been derived for various musical instruments should not be considered to represent the absolute truth. The musical instruments applied in the measurements are described in detail in [7], and they were played by named professional musicians. Examples of sound power levels and dynamic range of a few musical instruments are shown in Table 2.

Looking at the sound power factor in Table 2 it can be seen that one clarinet counts the same as two celli, and one trombone is equivalent to 25 celli in terms of emitted sound power at ***forte***.

Table 2. Examples of sound power levels at ***pp***, ***ff*** and ***f***, dynamic range and sound power factor ***k***.

Instrument	L_W (*pp*) dB	L_W (*ff*)	Dynamic range, *D*	L_W (*f*)	Sound power factor, *k*
	dB	dB	dB	dB	-
Violin	65	97	32	89	0.8
Viola	68	93	25	87	0.5
Cello	67	97	30	90	1.0
Double bass	75	97	22	92	1.6
Flute	77	96	19	91	1.3
Clarinet	74	101	27	93	2.0
Saxophone	87	101	14	98	6.3
Trumpet	87	106	19	101	12.6
Trombone	89	109	20	104	25.1

4 The room acoustic parameter strength G

The sound pressure level in a room is calculated under the usual assumptions of a combined direct and reverberant sound field, see e.g. Maekawa et al. [8, eq. (3.43)]:

$$L_p = L_W + 10\log\left(\frac{1}{4\,\pi\, r^2} + \frac{4(1-\alpha_m)}{S\,\alpha_m}\right) \cong L_W + 10\log\left(\frac{4(1-\alpha_m)}{S\,\alpha_m}\right) \text{ (dB)} \tag{5}$$

where $\boldsymbol{L_W}$ is the sound power level of the sound source, ***S*** is the total surface area (in m^2) and α_m is the mean absorption coefficient of all surfaces in the room. The approximation is valid for the distances outside the range of the direct sound field.

The amplification of the sound by the room is described by the term ***strength*** (symbol ***G***, in dB) and is defined in ISO 3382-1 [9, eq. (A.7)]. The strength is the sound pressure level in the room relative to the sound pressure level in a free field in the distance 10 m from the same source, which must be omni-directional:

$$G = L_p - L_{p,dir}(r_0 = 10\text{ m}) \text{ (dB)}$$

The strength of a room can be estimated from the mean absorption coefficient and the total surface area:

$$G = 10\log\left(\frac{4(1-\alpha_m)}{\alpha_m S}\right) - 10\log\left(\frac{1}{4\pi^2\, r_0^2}\right) \cong 31 + 10\log\left(\frac{4(1-\alpha_m)}{\alpha_m S}\right) \text{(dB)} \tag{6}$$

The surface area of the room is normally not known, but it can be estimated from the volume with sufficient accuracy. For this purpose the room is assumed to be of box shape with the ratio between length, width and height as:

$$\boldsymbol{L} : \boldsymbol{B} : \boldsymbol{H} = 1.6 : 1 : 0.8.$$

Thus the total surface area is:

$$S = 7.36 \cdot \left(\frac{V}{1.28}\right)^{2/3} \cong 6.243161 \cdot (V)^{2/3} \ (\mathrm{m}^2)$$

and the mean absorption coefficient is calculated from:

$$\alpha_m = \frac{0.161 \cdot V}{T \cdot S} \cong \frac{0.0258}{T} \cdot \sqrt[3]{V}$$

When ***G*** of a room is known it is possible to estimate the sound pressure level at ***forte*** in a room when the emitted sound power at ***forte*** of the music ensemble is known, by using the following relation ISO 3382-1 [9, eq. (A.9)]:

$$L_p(f) = L_W(f) + G - 31 \text{ dB} \tag{7}$$

As an example the sound power level of a classical symphony orchestra playing at ***forte*** is around 110 dB, and around 120 dB at ***fortissimo*** [4]. In order to obtain a sound pressure level at ***forte*** within the optimal range of 85-90 dB, this requires a hall with a strength ***G*** around 6 to 11 dB.

In general the sound pressure level at ***forte*** in a room with the strength ***G*** can be estimated using the sound power factor ***k*** for musical instruments as in Table 2 by the equation:

$$L_p(f) = G + 59 + 10 \log \textstyle\sum_i n_i \, k_i \quad (\text{dB}) \tag{8}$$

The method and the above equation (8) is the same as originally suggested by Meyer [4, 5, 6].

5 How to balance reverberation time versus strength

The acoustical coupling between musical instrument and room is very important and may affect the musical performance. An interesting example is described by Meyer [6, pp. 361-362], who refers to an experiment made by von Bekesy. He measured the vibration level of the piano strings while a trained pianist performed the same piece in three different environments. In the over-reverberant room the playing in the loud passages was somewhat weaker than in the neutral room, and in the room with dead acoustics the playing was more powerful. In the neutral (best) room the dynamic range during the performance was clearly bigger than in either of the rooms with too long or too short reverberation time. This finding suggests that in a room with insufficient acoustics the musical performance will suffer by a smaller dynamic range. Also the quality of the sound may suffer, as most instruments will create a sharper and less pleasant sound when forced to a higher sound power.

A simplified picture of the relation between room and music is shown in Figure 1. The acoustics of the room is characterised by two parameters, namely the reverberation time and the strength, which together makes a two-dimensional acoustical space. In this space there may be a region that is considered to optimal for a certain music type and ensemble of instruments. This kind of diagram was suggested by Nijs & de Vries [10], but with a system of curves representing the architectural parameters volume and mean absorption of materials.

The Figure 1 indicates that if the reverberation time deviates too much from the optimum range, the music will be either too dry or too muddy. On the other hand, if the room has a too high strength, the music will sound too loud and may be quite annoying, and if the strength is too low the music will sound weak and may thus be disappointing to listen to, not only for an audience but even for the performer.

As an example Nijs & de Vries [10] mentions (with reference to Leo Beranek) that the ideal European concert hall for a symphony orchestra should have a reverberation time between 2.0 and 2.3 s, and the strength should be between 4.0 and 5.5 dB. According to ISO 3302-1 [9] the JND (Just Noticeable Difference) is 1 dB for the strength and 5% for the reverberation time. Thus the above mentioned optimum range for symphonic music has a span of 3 JND in reverberation time and only 1.5 JND in strength.

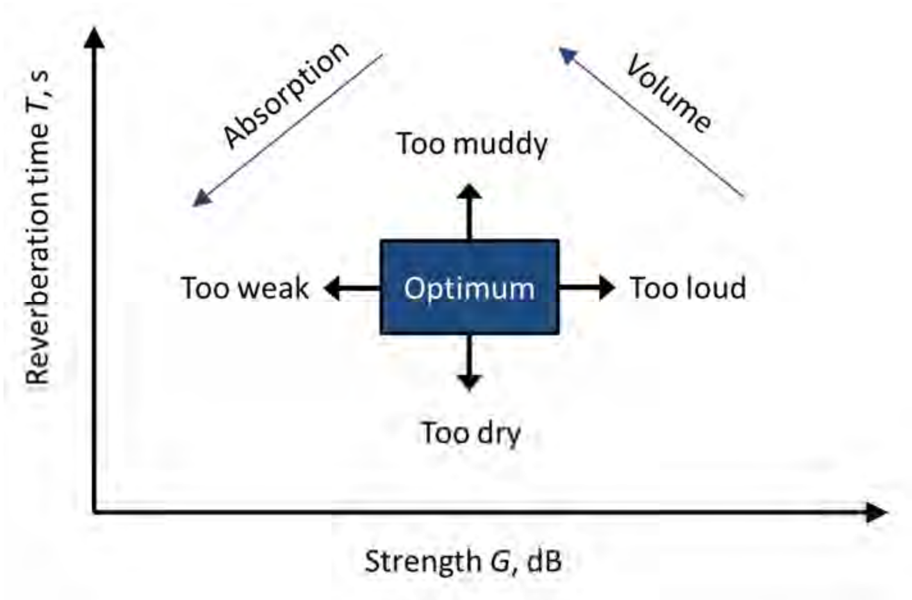

Figure 1. Principle of influence of the acoustic parameters reverberation time and strength on the perceived music.

In music rehearsal room the volume can be very small, and this is a major challenge to the strength. In order to avoid an extreme loud sound level it is necessary to make a considerable reduction in reverberation time. In other words, it is unavoidable to introduce a volume-dependent criterion for the maximum reverberation time. During the work on the standard NS 8178, several models for this volume-dependence were considered, and with a close look to the consequences for the strength parameter. In order that ***G*** should not exceed 25-26 dB it was found that the reverberation time must be rather short in small rooms. So, mainly in order to avoid the small rehearsal rooms to be too loud, it was concluded that the relationship is preferably in the form as originally suggested by Valk et al. [11]:

$$T = a \cdot \log(V) - b \quad (\text{s}) \tag{9}$$

The constants ***a*** and ***b*** have been selected for the minimum and maximum reverberation time as shown in Table 3. As it appears, different reverberation time limits as function of volume are defined for three kinds of music: amplified music, loud musical instruments, and weak musical instruments. Both rehearsal rooms and performance spaces are included, and with a shorter reverberation time in rehearsal rooms than in performance spaces.

Table 3. The constants ***a*** and ***b*** and the volume range for the reverberation time range limits.

Performance	*a*	*b*	Min *V* (m³)	Max *V* (m³)
Amplified music, min RT	0.250	0.150	300	6500
Amplified music, max RT	0.358	0.258	300	6500
Acoustic music, min RT (powerful instruments)	0.525	0.425	1500	6500
Powerful / weak instruments (max / min)	0.675	0.575	1500/600	6500
Acoustic music, max RT (weak instruments)	0.827	0.727	600	6500
Rehearsal	*a*	*b*	Min *V* (m³)	Max *V* (m³)
Amplified music, min RT	0.250	0.150	25	700
Amplified music, max RT	0.358	0.258	25	700
Acoustic music, min RT (powerful instruments)	0.404	0.304	40	3000
Powerful / weak instruments (max / min)	0.600	0.500	40/30	3000
Acoustic music, max RT (weak instruments)	0.750	0.650	30	3000

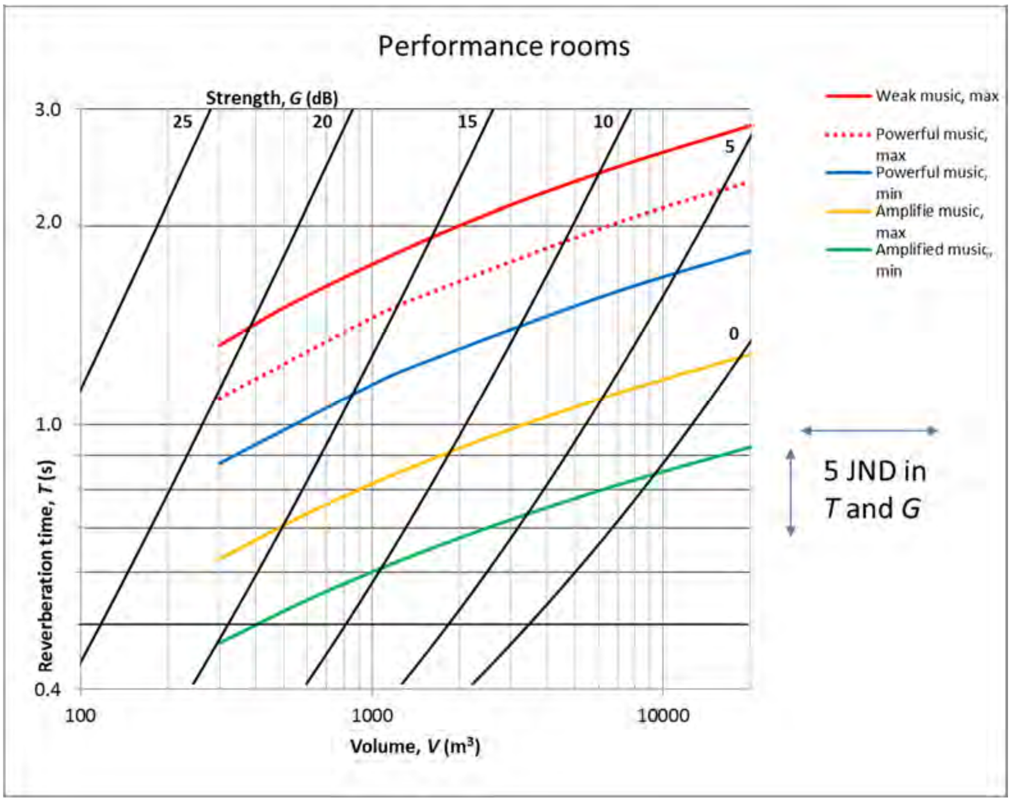

Figure 2. Upper and lower limits of reverberation time in performance spaces for the different kinds of music. The full lines indicate the strength parameter in 5 dB steps. Note that in this graph a logarithmic axis is used for the reverberation time. Approximate steps sizes for 5 JND are indicated to the right.

Upper and lower limits of reverberation time for performance spaces are shown as functions of volume in Figure 2. The reverberation time is understood to be the mid-frequency average of the 500 and 1000 Hz octave band values, in the fully furnished room but without an audience. Using a linear scale for the reverberation time the limiting curves will be straight lines, and they all meet at a point ($\boldsymbol{T}$ = 0.1 s and $\boldsymbol{V}$ = 10 m^3). However, in this figure a logarithmic axis has been used for the reverberation time, which makes sense because the JND for reverberation time is a relative step (5%). The approximate size of 5 JND in reverberation time as well as in strength is also indicated in Figure 2.

The two lower curves define the range for amplified music. These reverberation times are in agreement with the findings by Adelman-Larsen et al. [12] and are significantly lower than those given for acoustic music. Actually, there is a gap from the maximum reverberation time for amplified music to the minimum reverberation time for acoustic powerful music. This means that a hall made as a compromise reverberation time, will not be good for any music, but may rather be used for speech, instead.

For acoustic music the ranges for weak and powerful music are only separated by a dotted curve, which indicated that there is not always possible to make a clear distinction between these two types of music ensembles.

6 Examples

Four examples of music rehearsal rooms are discussed in the following. The aim is to find the volume and reverberation time that corresponds to a sound level at ***forte*** between 85 and 90 dB.

6.1 A string quartet

The string quartet with two violins, viola and cello yields a total sound power factor of 3.1 and a sound power level at ***forte***, $\boldsymbol{L_W(f)}$ = 95 dB. Thus, from eqn. (7) is found that $\boldsymbol{G}$ should be between 21 and 26 dB. The range for weak instruments in Figure 3 leads to a volume from 30 to 200 m^3 and $\boldsymbol{T}$ between 0.4 and 1.1 s, depending on the volume. See the blue area in Figure 3. If the string quartet is playing in a room with a volume exceeding 200 m^3 the sound level will be rather weak.

6.2 A boys choir

A boys choir with 24 singers yields a sound power level at ***forte***, $L_W(f)$ = 102 dB. Thus, from eqn. (7) is found that ***G*** should be between 14 and 19 dB. The range for weak instruments in Figure 3 leads to a volume from 330 to 1 600 m^3 and ***T*** between 1.1 and 1.7 s, depending on the volume. See the green area in Figure 3.

6.3 A brass quintet

The brass quintet with 2 trumpets, 2 trombones, and 1 tuba yields a sound power level at ***forte***, $L_W(f)$ = 110 dB. Thus, from eqn. (7) is found that ***G*** should be between 6 and 11 dB. The range for powerful instruments in Figure 3 leads to a volume from 2 000 to 10 000 m^3 and ***T*** between 1.0 and 1.9 s, depending on the volume. See the red area in Figure 3.

6.4 A band with 40 musicians

The band has 6 flutes, 9 clarinets, 1 bass clarinet, 4 saxophones, 4 trumpets, 3 French horn, 4 trombones, 2 euphonium, 3 tuba and 4 percussion. This yields a sound power level at ***forte***, $L_W(f)$ = 116 dB. Thus, from eqn. (7) is found that ***G*** should be between 0 and 5 dB. The range for powerful instruments in Figure 3 leads to a volume from 8 000 m^3 or more, and ***T*** between 1.3 and 2.0 s, depending on the volume. See the yellow area in Figure 3. However, 8 000 m^3 is a big room, and a smaller volume might be considered; with 2 500 m^3 and ***T*** = 1.1 s the sound level at ***forte*** will 95 dB, which is 5 dB above the preferred maximum.

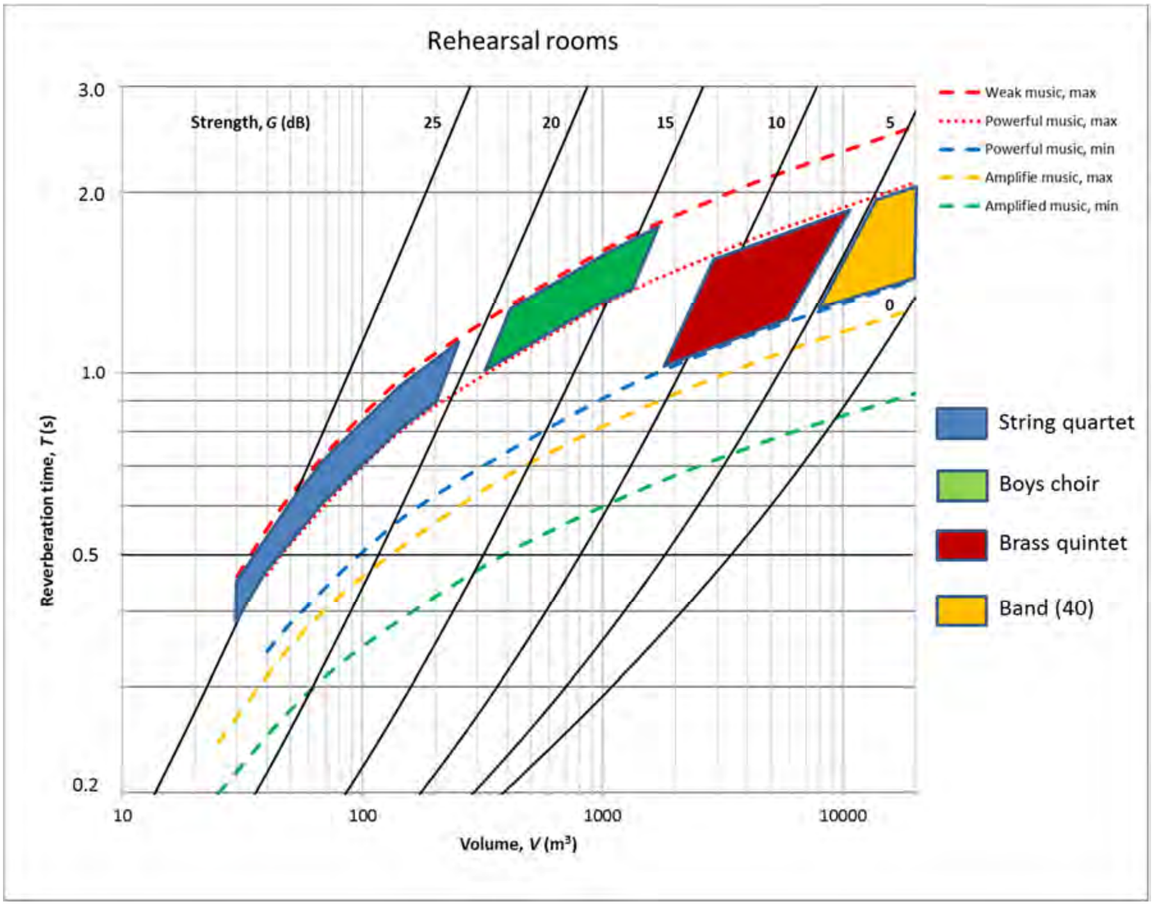

Figure 3. Upper and lower limits of reverberation time in rehearsal rooms as functions of volume (dotted curves). The full lines indicate the strength parameter in 5 dB steps. The four ranges shown refer to the examples discussed in the text.

7 Discussion

Although not mentioned above, the frequency dependency of the reverberation time is also an important issue that is dealt with in the standard [2]. Tolerance curves are presented to define the acceptable variation in octave bands from 63 Hz to 4000 Hz.

In addition to the requirements for reverberation time as explained above, the standard [2] contains a number of Tables that specify requirements on minimum volume, ceiling height, and treatment of surfaces with absorption and scattering structure. One important design detail is the angling of walls in small rehearsing and ensemble rooms in order to avoid flutter echo and/or colouration.

Another important parameter is the ceiling height in rehearsal rooms; for amplified music up to 180 m^3 the minimum ceiling height is 2.4 m, and in rehearsal room for non-amplified musical instruments the minimum is 2.7 m, increasing to 3.5 m in small ensemble rooms. In larger volumes the minimum ceiling height is bigger. There are several reasons for this, not only related to the sound level created in the room, but also very much related to the sound quality, i.e. avoiding too strong colouration due to reflections from a surface that is too close to the sound source.

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