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The influence of the orchestra on stage acoustics

R.H.C. Wenmaekers[1,2], C.C.J.M. Hak[2], L.C.J. van Luxemburg[1,2]

[1] Level Acoustics bv., De Rondom 10, 5612AP, Eindhoven, The Netherlands
[2] Eindhoven University of Technology, Department of Architecture, Building and Planning, Unit Buildings Physics and Systems, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Email: r.h.c.wenmaekers@tue.nl

Abstract

The available stage acoustic parameters measure the energy ratio between certain time intervals derived from an impulse response. The parameter time intervals may be based on typical sound paths on a stage. A study of typical sound paths and their time intervals indicates that a transition time point may exist between early reflected sound and late reflected sound at approximately 100 ms and that this transition time point is measured relative to the 'departure' of the sound from the sound source.

However, the current choices for the time intervals in the available parameter formulas do not agree. There are two types of transition time points that reflect certain stage acoustical aspects related to a stage for a symphonic orchestra. The first is the transition time point between direct sound and reflected sound 'x' and the second is the transition time point between the early reflected sound and late reflected sound 'y'. The effect of the choice of transition time points is investigated for $G_{x\text{-}y}$, $G_{y\text{-}inf}$ and $LQ_{x\text{-}y}$ from measured impulse responses. It is shown that the direct sound should be omitted to measure differences between halls and that different choices of time intervals do not result in large differences in the ranking of 7 concert hall stages.

All parameters are commonly determined on an unoccupied (empty) stage, preferably with chairs and stands. In this paper, results of measurements on an occupied stage are presented which show large differences between empty and occupied stages. These measurements also indicate that a fixed time interval relative to the time of departure of the sound seems most appropriate.

1. Introduction

For a long time, acousticians have been focusing on the acoustics in the hall from an audience point of view judging reverberance, clarity and spaciousness, summarized by Barron [1] and Beranek [2]. More recently, the importance of good acoustics on stage is recognized by musicians as well as acousticians [3-15]. This is referred to as stage acoustics. For musicians on stage three factors are important: (1) the hearing of yourself, (2) the hearing of others and (3) the hearing of the hall. The challenge in designing excellent stage environments and concert halls is to find a good balance between these factors. A good balance is important for the orchestra to easily play ensemble but also to avoid excessively high sound pressure levels [16-20].

In the last decade, safety and health agencies are working with musicians, conductors and orchestra directors on controlling the noise exposure of members of professional orchestras [21, 22]. To reduce the noise levels, measures are proposed like the introduction of screens and risers within the orchestra or even ear plugs [20, 23]. A study in 2003 by Peutz [24] showed the importance of the stage environment on the occurring noise levels. In this study, a comparison has been made between the noise levels within the orchestra in an orchestra pit and on an open stage while playing the same musical piece. Differences up to 3 dB (the double of the energy) were found caused by the different stage acoustic environments. This proves that good stage acoustics is important from a musical as well as an occupational health point of view.

Sound paths on stage

An example of typical sound paths on a concert hall stage related to hearing yourself, others and the hall is illustrated in figure 1. The sound can either follow the paths directly through the orchestra or indirectly via a number of reflection paths. Musicians of symphonic orchestra seem to benefit from reflections that arrive relatively early after the direct sound to improve ensemble playing. Also, increasing the direct sound transfer and available sightlines can be beneficial, which may be achieved by introducing risers. In general, the late arriving reflections seem important for a sense of feedback from the hall.

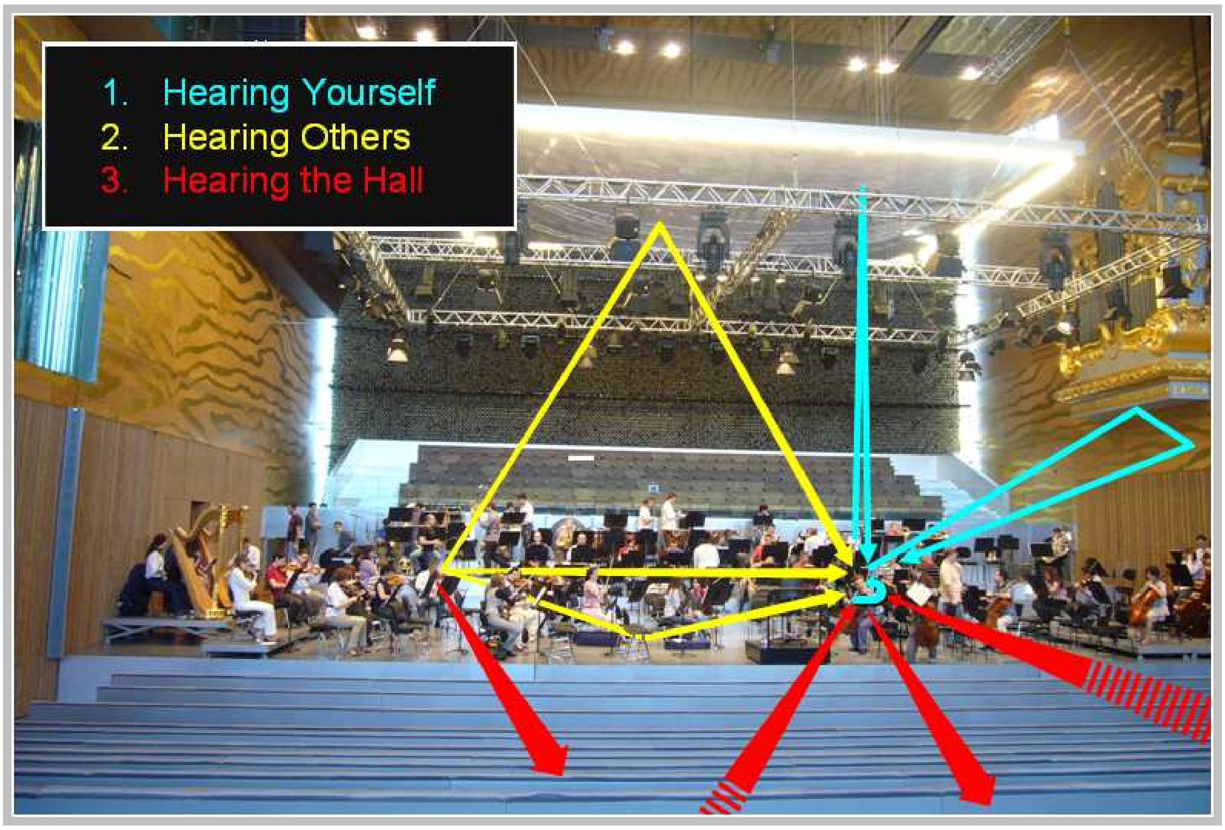

Figure 1: Sound paths on the stage of concert hall Casa da Musica

Figure 2 illustrates the time intervals of sound paths on a typical stage of 20 meters wide, 12 meters deep and a canopy at 10 meters height. The direct sound of ‘yourself’ arrives at the musician at t =1 ms (blue dot) and the 1st order early reflections of ‘yourself’ can arrive within 100 ms (blue dashed line). The direct sound of ‘others’ can arrive 4 to 60 ms after the ‘departure’ of the sound from the sound source, depending on the mutual distance of 1 to 20 m (yellow dots). When the mutual distance between musicians increases, the time window of their early arriving 1st order reflected sound from stage surroundings narrows. However, most early 1st order reflected sound from ‘others’ also arrives within 100 ms after the departure of the sound (yellow dashed lines). Most late reflected sound coming back from the hall may arrive after 100 ms. This indicates that a transition time point may exist on stage between early reflected sound and late reflected sound at approximately 100 ms and that this transition time point is measured relative to the departure of the sound from the sound source(s).

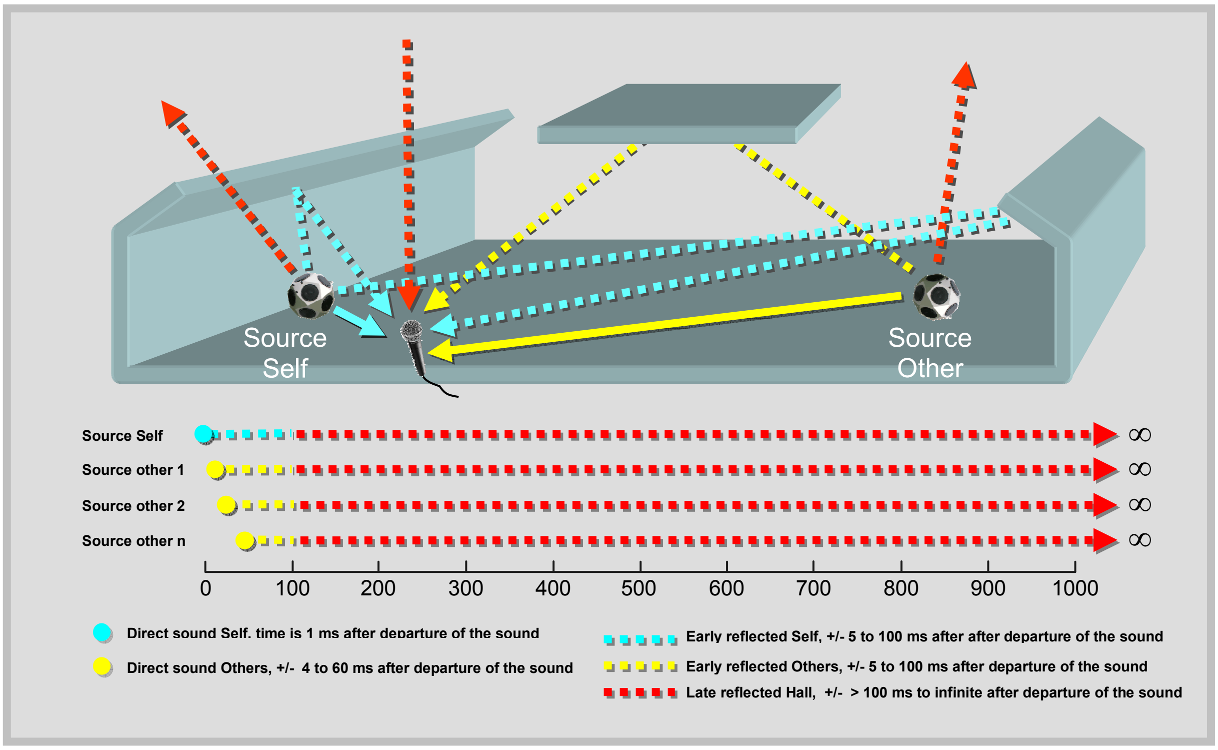

Figure 2: Typical time intervals of sound paths on a stage

Available stage acoustic parameters

To investigate stage acoustics, several objective parameters have been proposed. The first objective stage acoustic parameters Early and Late Support are a result of a study in Danish Concert halls by Gade [25, 26, 27]. Some of these stage acoustic parameters are also mentioned in the ISO 3382-1 [28] and more parameters have been proposed [10, 13, 15]. Some parameters describe the amount of support from early reflections on stage which can be beneficial for playing ensemble, like ST_{early}, EEL, G_{7-50} and G_{5-80}. Another group of parameters describe the amount of support of sound coming back from the hall, like ST_{late}, CS and G_{late}. A combination of both is summarized in the LQ_{7-40} which describes the ratio between early to late reflected sound.

These stage acoustic parameters measure the energy ratio between certain time intervals derived from an impulse response. Some time intervals may be based on the typical time intervals found on stages, as shown in figure 2. Other time intervals may have been chosen based on results from perceptive studies with musicians. For instance, a time interval of 17 to 35 ms after the direct sound has been suggested as useful for playing ensemble in a trio [3]. Most parameters are determined from an energy ratio as illustrated in figure 3. For every available parameter, the parameter formula is described in the text and is illustrated graphically. For instance, the Early Support (ST_{early}) is determined by 10 times the logarithm of the ratio between the reflected sound energy (20 to 100 ms) and the direct sound energy (0 to 10 ms) at one meter from 'yourself'. However, it has never been investigated whether the 100 ms time limit is the optimal choice for the ST stage parameters [39].

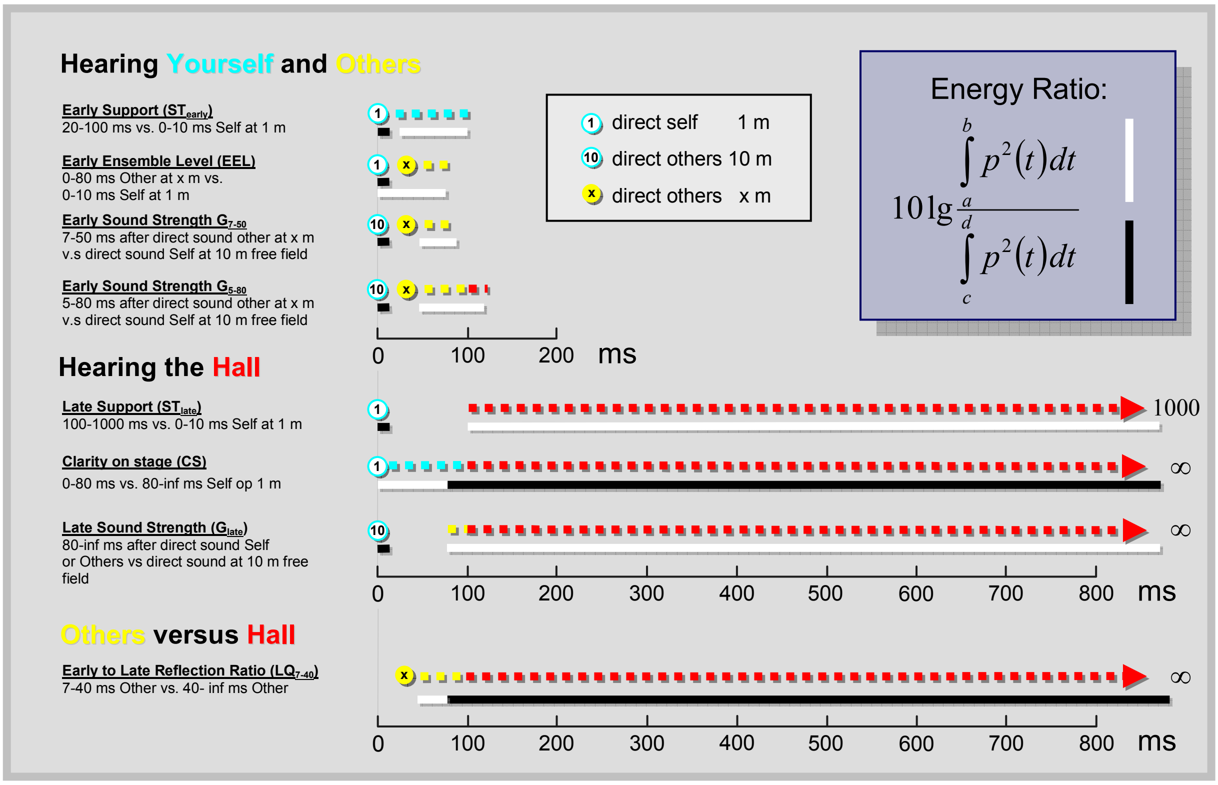

Figure 3: Some stage acoustic parameters based on energy ratios

ST_{early}, ST_{late} and CS must be measured at 1 meter distance from the sound source (musicians position), and EEL, $G_{7\text{-}50}$, $G_{7\text{-}80}$ and $LQ_{7\text{-}40}$ are to be measured with larger source to receiver distances corresponding to two musicians positions, as illustrated in figure 4 [29]. Also, there is a difference in definition between the parameter ST_{early}, ST_{late}, CS and EEL, whose time intervals are defined relative to the arrival of the direct sound at 1 m distance of 'yourself' (≈ departure of the sound), and the time intervals of $G_{7\text{-}50}$, $G_{7\text{-}80}$ and $LQ_{7\text{-}40}$, which are defined relative to the arrival of the direct sound at a certain distance 'x'. Based on the study of time intervals of sound paths on a typical stage, it seems most appropriate to define time intervals relative to the departure of the (direct) sound. However, a parameter that omits the direct sound and is measured at a distance 'x' can not easily be defined relative to the time of departure of the (direct) sound.

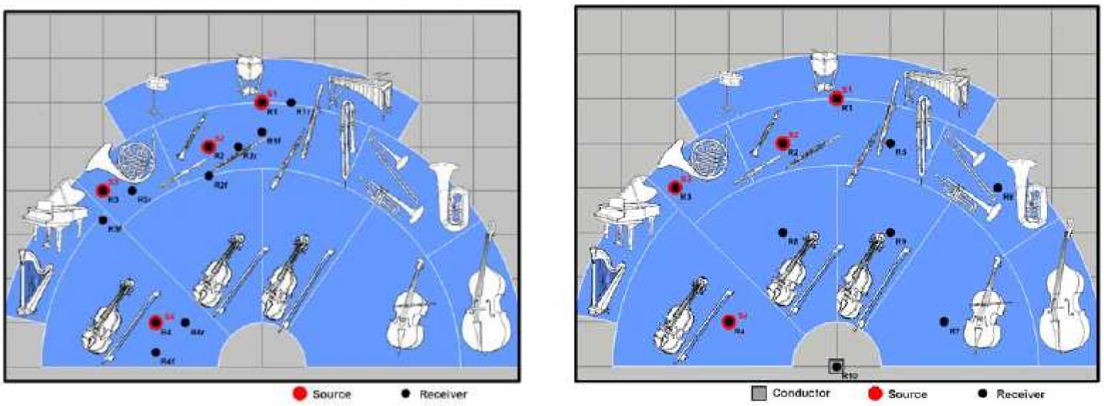

Figure 4: Receiver positions at 1 meter distance from the sound source (left) or combinations of source and receiver positions based on the instrument positions (right) [29]

In some parameter formulas a time interval to infinity is used. For the late support, 1000 ms has been chosen as 'time to infinity' [25, 26]. This method has been validated by Hak & Vertegaal [42] showing that in case of a concert hall (RT ≈ 2 s) errors much smaller than 1 dB occur when choosing at least half the reverberation time as the time for infinity in the energy ratio parameter formula of C_{80}. This may also be true for the ST_{late} parameter.

2. Problems related to stage acoustic measurements

The available stage acoustic parameters seem valid with respect to the musicians hearing themselves, others and the hall [30, 3, 31]. Also, the sound strength G seems valid for assessing loudness [32, 33]. Some research has been performed by Gade [26], Dammerud [15], Giovannini [14], Luxemburg et al. [29] and others, trying to correlate subjective opinions evaluated by questionnaires to results of measured objective parameters in various halls. However few satisfying correlations have been found between the musician's judgment of stage environments and the available objective parameters. Also, little correlation has been found between architectural measures of stage surrounding [34, 26, 35, 36, 37, 38].

It proved to be hard to get reliable and reproducible musicians' opinions about stage acoustical experiences. This is because experienced musicians often are very well trained to adapt to various kinds of acoustic environments. Also, judging stage acoustics may be biased by the reputation of the hall from a listeners' or historic point of view and other non acoustic parameters like climate conditions and available space which can be more important than acoustic parameters. More research is needed to improve reliable subjective evaluation methods [39, 40, 14].

On the other hand, many researchers found uncertainties in the available measurement methods and equipment used to measure stage acoustic parameters [14, 15, 39, 41, 42, 43, 33, 44, 45, 46]. Among other things these uncertainties may be caused by the following metrological issues:

- The directivity of the common standard sound source is not fully omnidirectional, which is a problem measuring close to the sound source [44]. This is always the case when measuring on stage. The directionality affects most energy ratio parameters.
- Some parameters use the direct sound measured on stage to determine the sound power of the sound source (ST_{early}, ST_{late}, EEL), others use a sound power measurement in the laboratory as a reference ($G_{7\text{-}50}$, $G_{7\text{-}80}$, G_{late}). Research by Hak et al. [33] has shown that the results obtained by these methods can differ significantly.

Also, the influence of the orchestra on the stage is not taken into account in the current methods. The following related problems need further investigation:

- All parameters are commonly determined by using an omnidirectional sound source and microphone. However, most musical instruments are highly directional above 500 Hz octave band frequency [6]. Also, musicians make use of directional hearing by their ears. No practical method has been proposed to take into account instrument and listeners directionality.
- The symphonic orchestra consists of more than 80 instruments playing in various groups [6]. Current single or average results from stage acoustic measurements do not

take into account the number of instruments and the properties of those instruments like sound power, directivity and frequency spectrum [39].

- The current choices for the time intervals in the available parameter formulas do not agree. Research has shown that a different choice of time intervals for $LQ_{7\text{-}40}$ can affect average ranking of different stages on stage acoustic performance [12]. Additional results will be presented and discussed in this paper.
- All parameters are commonly determined on an unoccupied stage, preferably with chairs and stands. But, research by O'Keefe [45] and Dammerud [15] has shown that the attenuation of sound of the orchestra on stage should be taken into account. In this paper, results are presented of measurement on an occupied stage which show large differences between empty and occupied. No practical method has been proposed yet to perform stage acoustic measurements taking into account the attenuation of the orchestra, without a full orchestra being present on stage.

3. The influence of the orchestra

Time intervals

The time intervals used in the different parameter formulas do not agree (see figure 3). There are two types of transition time points that reflect certain stage acoustical aspects related to a stage for a symphonic orchestra.

1. The first is the transition time point between direct sound and reflected sound, which varies in the different parameter formulas from 5, 7 to 10 ms. The floor reflection may typically arrive within 7 ms. A gap between 10 and 20 ms is used in the ST_{early}, which has been introduced to avoid the overlap of filters when using certain measurement techniques [25, 26].
2. The second is the transition time point between the early reflected sound and late reflected sound, which varies in the different parameter formulas from 40, 50, 80 to 100 ms. In most parameter formula's this time point is relative to the time of arrival of the direct sound at the receiver position, except for the parameter EEL where this time point is relative to time of departure of the sound at the sound source.

In this research, the first transition time point is denoted with 'x', the second transition time point is denoted with 'y' and time to infinity is denoted with 'inf'. From this, two types of sound strength parameters $G_{x\text{-}y}$ and $G_{y\text{-}inf}$ can be formulated, where x and y can be varied. Also the difference between $G_{x\text{-}y}$ and $G_{y\text{-}inf}$ can be calculated which is denoted as $LQ_{x\text{-}y}$.

In this research, the effect of the choice of transition time points is investigated for parameters that are measured at a distance from the sound source. This is done by deriving 16 different parameter values for $G_{x\text{-}y}$, $G_{y\text{-}inf}$ and $LQ_{x\text{-}y}$ from measured impulse responses from 7 different Dutch concert hall stages A to G as described in [29]. The average mid-frequencies values (500 and 1000 Hz) have been calculated for 36 combinations of 4 source (S) and 9 receiver (R) positions per stage (see figure 4, right picture). For every source and receiver combination, 4 impulse responses have been measured while rotating the omnidirectional sound source in equal steps of 90 degrees, which resulted in a standard deviation of $\sigma_{\text{average of } 36} \leq 0.4$ dB and $\sigma_{\text{max of } 36} \leq 1.2$ dB for the mid-frequency range. The mutual distance between S and R positions varies between 2 and 10.6 meters and is on average 5.3 meters. In total >32,000 parameter values were calculated from >1,000 measured impulse responses with the room acoustic measurement software Dirac 5.0 (B&K Type 7841).

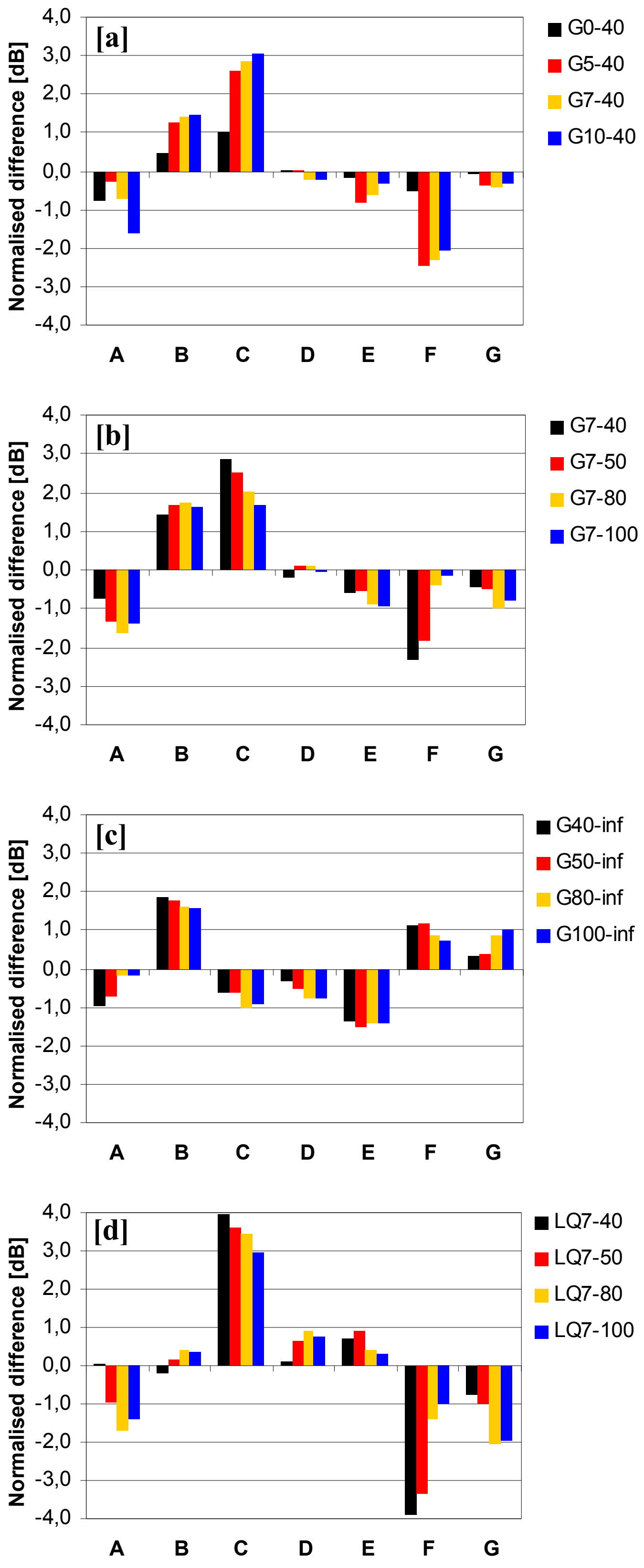

Figure 5: Gx-y, Gy-inf and LQx-y concert hall stages A to G

Figure 5 shows four graphs of normalized results for measured parameters for the 7 different concert hall stages A to G:

Graph [a] shows the $G_{x\text{-}40}$, with x = 0, 5, 7 or 10 ms and a fixed value y = 40 ms. The fixed 'y' of 40 ms is chosen to make the parameter most sensitive to changes of 'x'. The results in graph [a] shows that when the direct sound is included (x=0), the difference between the stages is very small. However, when (a part of) the direct sound is omitted, larger differences are found between concert hall stages. The ranking of the halls does not change with x = 5, 7, or 10 ms, except for stage A*.

Graph [b] shows the $G_{7\text{-}y}$, with a fixed value x = 7 ms and with y = 40, 50, 80 or 100 ms. A fixed 'x' of 7 ms is chosen as an average value of 5, 7, and 10 ms. When comparing the stages, the ranking of the different stages does not change with different values of 'y', except for stage F*.

Graph [c] shows the $G_{y\text{-inf}}$, with y = 40, 50, 80 or 100 ms. When comparing the stages, the ranking of the different stages does not change with steps larger than 1 dB.

Graph [d] shows the $LQ_{7\text{-}y}$ with y = 40, 50, 80 or 100 ms. A fixed 'x' of 7 ms is chosen as an average value of 5, 7, and 10 ms. When comparing the stages, the ranking of the different stages changes with different values of 'y' for stage A, F and G*.

It is shown that the direct sound should be omitted to measure differences between halls and that different choices of time intervals do not result in large differences in the ranking of 7 concert hall stages for sound strength parameters.

* Changes larger than 1 dB

Attenuation of sound by the orchestra

The stage acoustic parameters have been measured on the 7 concert hall stages on an unoccupied empty stage. However, direct and early reflection sound paths are usually obstructed by the orchestra members on stage [48, 40]. Most of the available stage acoustic parameters measured on an empty stage do not take into account the attenuation of sound by the orchestra obstruction. In figure 6, it is shown that most parameters are likely to be influenced by the orchestra (highlighted in red rectangles), except for ST_{late}.

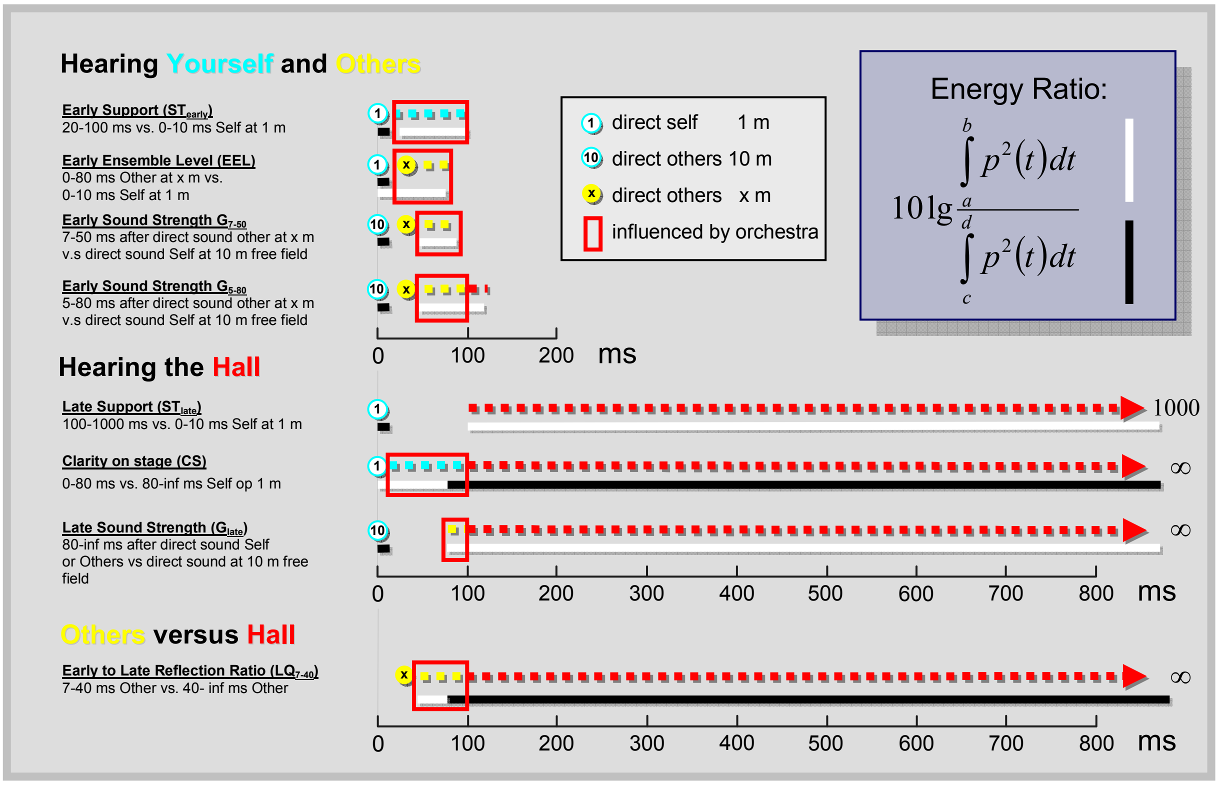

Figure 6: Stage acoustic parameters with time intervals that are likely to be influenced by orchestra attenuation

To investigate the influence of the attenuation by the orchestra on the measured impulse response, measurements have been performed with and without a full orchestra on stage for source and receiver combination S1R4 on stage A and stage C [29]. An additional measurement on the empty stage C was performed, while all sound absorbing seats in the hall were removed (RT ≈ 4.0 s). In all cases no audience was present in the hall. Stage A is a concert hall with no reflecting surfaces around the stage and has a disputable reputation in terms of stage acoustics. Stage C is a concert hall with many reflecting surfaces around and above the stage and has a good reputation in terms of stage acoustics. The source to receiver distance is 8 meters, which results in a 23 ms delay of direct sound, see figure 7. An overlay of the measured decay curves (all pass) is presented in figure 8 for stage A and in figure 9 for stage C.

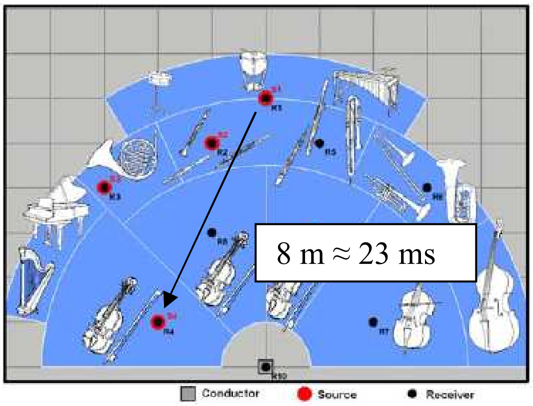

Figure 7: source and receiver position S1R4

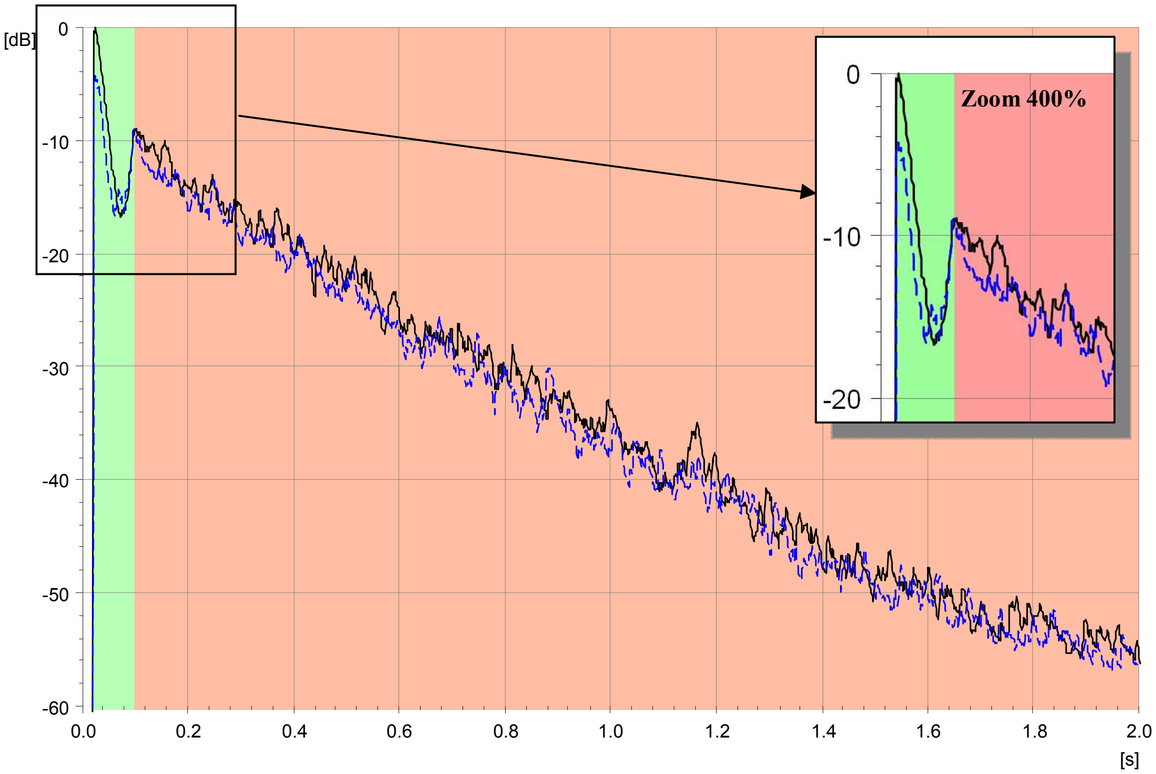

Figure 8: Decay curve of stage A with an empty stage (black) and an occupied stage (blue)

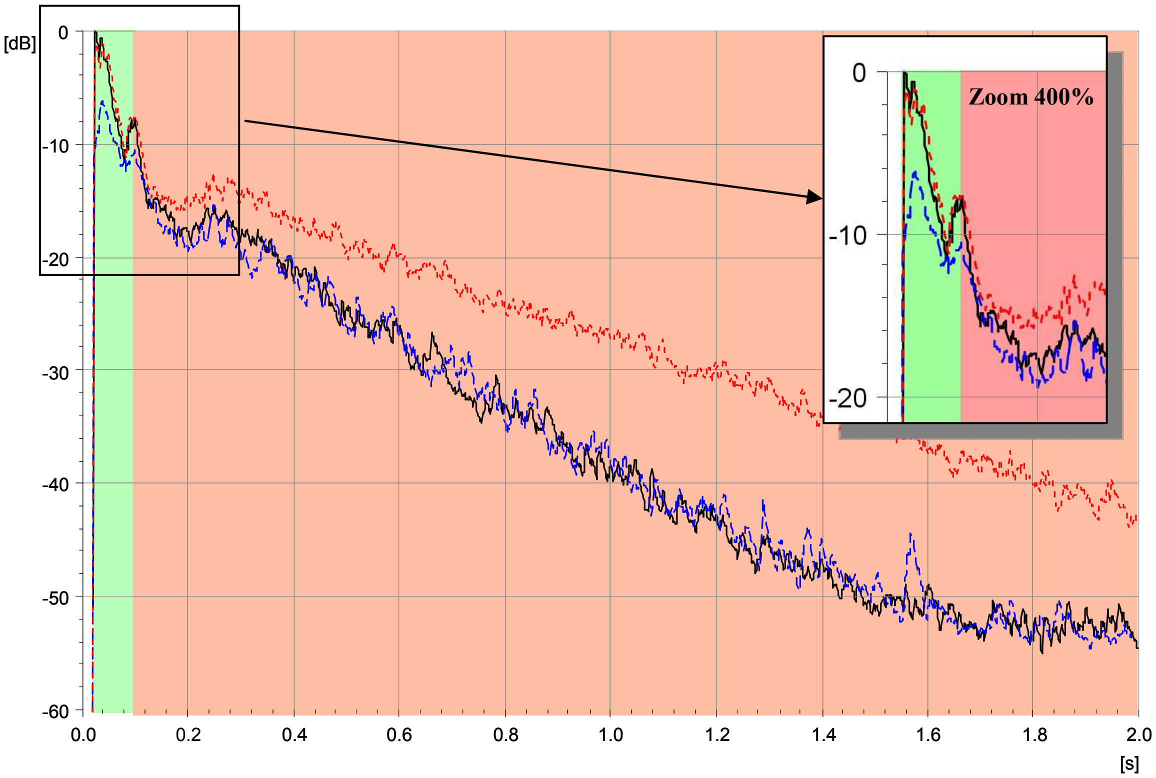

Figure 9: Decay curve of stage C with an empty stage (black), an occupied stage (blue) and an empty stage and the hall without seats (red)

The decay curves in figure 8 of stage A show that after the direct sound, arriving at t = 23 ms, there is a gap until approximately t = 100 ms. This may be explained by the lack of reflecting surfaces around the stage. When comparing the decay curve of the empty stage with the occupied stage, a difference of +/-4 dB in direct sound occurs. After the direct sound, no clear difference occurs.

The decay curves in figure 9 of stage C show that after the direct sound, arriving at t = 23 ms, there is a strong package of reflections between t = 80 and 100 ms. This may be explained by the large amount of reflecting surfaces around the stage, among which are sound diffusing elements. Comparing the decay curve of the empty stage with the occupied stage, a difference of +/-6 dB in direct sound occurs. Also, the direct sound builds up gradually, which is a typical effect that can be expected when the receiver does not 'see' the source because of an obstruction [41]. However, not only the direct sound level is reduced by the orchestra, but also the early reflected sound level between 80 and 100 ms is reduced by at least 2 dB.

On stage A and stage C, after 100 ms the decay curves are more or less identical on a empty or occupied stage, which may indicate that the late reflected sound is not much influenced by the orchestra on stage. A remarkable result is found, when comparing the decay curves of stage C with and without sound absorbing seats in the hall. It clearly shows that the absence of seats is only of influence on the decay curve after 100 ms on stage! This indicates that indeed discrimination may exist between the stage and the hall, where early 'stage' reflections arrive before 100 ms and late 'hall' reflections arrive after 100 ms after departure of the sound from the sound source.

Conclusions

Most stage acoustic parameters seem valid to measure a certain amount of sound energy transferred from a source to a receiver on stage. However, the available measurement methods need further development in terms of reliability. Also, the influence of the orchestra is not yet taken into account by the current measurement methods and parameters. In this research, the choices of the time intervals in parameter values have been investigated. It is shown that the direct sound should be omitted when measuring the average early sound energy of various source receiver distances on an empty stage.

Different choices in time interval point 'x' of 5, 7, and 10 ms and 'y' of 40, 50, 80 and 100 ms in the early reflected sound strength $G_{x\text{-}y}$ and the late reflected sound strength $G_{y\text{-}inf}$ do not result in a different ranking of 7 concert hall stages. This indicates that most parameters are likely to be highly correlated. However, for the ratio between early and late reflected sound energy $LQ_{x\text{-}y}$ differences larger than 1 dB occur in average stage values.

Current available parameters that omit the direct sound use a fixed time interval relative to the time of arrival of the direct sound. In this study, typical delays of 1^{st} order reflections on a stage and measurements on stage in a concert hall with and without seats in the hall indicate that a fixed time interval relative to the time of departure of the direct sound seems more appropriate. This approach might also be more realistic from a perceptive point of view, because the total listeners' time interval is fixed and does not depend on the distance between the source and receiver. Also, 100 ms seems a valid transition time point to discriminate between 'stage' reflections and 'hall' reflections from an architectural point of view.

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