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Early and Late Support over various distances: rehearsal rooms for wind orchestras

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Summary

Ensemble conditions within orchestras are often evaluated using the Early and Late Support parameters. While the original parameters are to be measured at a distance of 1 m between source and receiver, extended Support parameters ST_{early,d} and ST_{late,d} have been introduced that can be used to measure the amount of early and late reflected energy at various source and receiver distances. In previous studies, results of these parameters for various concert halls and orchestra pits have given new insights on the distribution of reflected sound on stage. Additionally, in this paper, measured results will be presented for a number of rehearsal rooms, as typically used by both professional and non-professional Dutch wind orchestras. In these rooms, the reverberation time is controlled by added sound absorption, either applied to the walls, ceiling or both. In some rooms the ceiling or walls are made diffusive. Results for ST_{early,d} show that, compared to concert hall stages, (much) more early reflected sound energy is present in these rehearsal rooms. A similar increase was found for measurements in the covered part of orchestra pits. There is a moderate decay of ST_{early,d} over distance, which results in an equal distribution of early sound energy over the orchestra. Additionally, the ST_{late,d} shows that the amount of late reflected sound energy is similar to that on concert hall stages, even though the reverberation time is lower. Especially the higher level of early reflected sound in rehearsal rooms, for all possible source to receiver distances, will contribute more to the total sound exposure of the musicians than on concert hall stages. The contribution of late sound to the sound exposure is expected to be in the same order of magnitude.

PACS no. 43.55.+p, 43.58.+z, 43.75.+a

1. Introduction

In the Netherlands, many musicians play in a non-professional wind orchestra. Especially in the southern part of the country, almost every village has its own wind orchestra and many larger towns have multiple orchestras. The wind orchestras are divided into three groups: the concert band or ‘harmonie’, with a mix of woodwind and brass instruments; and the fanfare and brass band, both only having brass instruments. These bands are accompanied by a percussion group, who in most cases also form a separate full percussion orchestra. In total, over 2400 orchestras and ensembles are member of the Royal Dutch Music Association (KNMO).

Most of these orchestras have a weekly rehearsal in their local hall (in Dutch: the ‘harmoniezaal’ or ‘fanfarezaal’), which is a dedicated room for the orchestra to rehearse and perform. Typically, the wind and percussion orchestra share the same rehearsal and performance space. Often, these halls also act as a community center resulting in multifunctional demands for the use.

Most of the halls are not purpose built for the orchestra only, and, as the building budget is often limited, they are being built by local architects and contractors, often members of the same community. Only recently, acousticians are (sometimes) involved in the design process. However, few is known about the acoustic characteristics of these halls and the demands of these orchestras for such halls. In this paper, 7 rehearsal rooms have been investigated using state-of-the-art room acoustic measurement methods. Specifically, stage acoustic measurements have been performed and the recently introduced Extended Support parameters have been studied.
2. Methods

2.1. Parameters

The most common objective room acoustic parameters to investigate stage acoustics are the ST$_{early}$ and ST$_{late}$ based on research by Gade$^{1,2}$ and described in ISO 3382-1$^{3}$. These parameters are typically derived from impulse responses, measured at 1 meter distance from an omnidirectional sound source. Recently, Wenmaekers et al.$^{4}$ proposed to modify and extend the commonly used ST parameters so they can be measured at various source to receiver (S-R) distances, denoted ST$_{early,d}$ and ST$_{late,d}$. This is done by introducing a variable time point ‘103-delay’ that takes into account the delay of direct sound by increased distance, see equation (1) and (2), where the ‘delay’ is the S-R distance divided by the speed of sound. This way, the parameters can be measured at S-R distances up to 25 m, considering a time interval width of 30 ms as an acceptable minimum. The time interval of early reflected sound starts at 10 ms instead of 20 ms to be able to measure closer to the stage boundaries up to 2 m. The reference level at 1 meter distance is measured separately at only one position free from reflective walls are ceilings; see Wenmaekers et al.$^{4}$ for more background information and literature.

$$ST_{early,d} = 10 \log \left( \frac{\int_{0}^{103-\text{delay}} p_d^2 \, dt}{\int_{0}^{10} p_{1m}^2 \, dt} \right)$$

(1)

$$ST_{late,d} = 10 \log \left( \frac{\int_{0}^{\infty} p_d^2 \, dt}{\int_{0}^{103-\text{delay}} p_{1m}^2 \, dt} \right)$$

(2)

where, $p_d$ is the sound pressure measured at distance $d$; $p_{1m}$ is the sound pressure measured at 1 m distance; and delay is the S-R distance divided by the speed of sound; time to infinity is defined as the time of the cross point between the decay curve and the noise floor of the impulse response.

An important finding from previous research on 11 concert hall stages$^5$ and an orchestra pit$^6$ is that ST$_{early,d}$ decays over distance and that this decay correlates well with a logarithmic trend line. In contrast, ST$_{late,d}$ does not depend on distance and an average value over all positions or ST$_{late}$ measured only at 1 m can be considered.

2.2. Positions

Impulse response measurements have been performed on a grid of source and receiver positions over ‘the orchestra area’. In earlier research on stages of symphony orchestras$^4$ a grid with fixed dimensions was used, see figure 1a. However, it was found that in most rooms used by wind orchestras, the available space is much smaller (120 m$^2$ instead of 200 m$^2$ on average). The various sections in the wind orchestra are distributed in a similar way as in the symphonic orchestra. So, the same distribution of positions was used in this research, but with scaled down dimensions, see figure 1b.

![Figure 1: measurement positions (a: symphony orchestra, b: wind orchestra)](image-url)
2.3. Measurements

Impulse response measurements have been performed using an omnidirectional sound source AE type Pyrite, an amplifier AE type Amphion and B&K type 4189-A-021 microphones using Dirac 6.0 (B&K Type 7841) measurement software. For each combination of source and receiver, multiple measurements were taken while rotating the sound source stepwise in 5 equal-angular steps. To further reduce measurement uncertainty, all impulse responses have a decay range INR^2 of at least 45 dB. The source height was 1.35 m and the receiver height was 1.20 m (except for R10 where the height was 1.95 m). All parameters results for ST_{early,d} and ST_{late,d} were averaged over the 250 to 2000 Hz octave bands. No chairs or stands were put in the orchestra area (empty ‘stage’), further investigations will be performed on this topic in the near future.

2.4. Image Source Method

To investigate the contribution of the various reflecting surfaces to the total early reflected sound level within the 10-103 ms time window (equal to ST_{early,d}), the Image Source Method (ISM) has been used. It was found that, to be able to investigate the sound level in the time window up to 103 ms after departure of the sound, only the 1st and 2nd order reflections need to be taken into account. For every 1st and 2nd order reflection, the sound path length from source to receiver ‘d’ in meters is calculated. Then, the sound level of each reflection is determined using the inverse square law -20lg(d), while taking into account the level reduction due to sound absorption by a factor -10lg(1/(1-\alpha)). The direct sound and first floor reflection were discarded as they arrive within the 0-10 ms time window. An average value over the 250-2000 Hz octave bands is considered. Because of the relatively high frequency range, the energy of different sound paths were summed energetically. The exception to this rule are the 2nd order reflected sound paths that arrive twice with the same pathlength (like the floor-ceiling path and ceiling-floor path); here the sound energy was considered to arrive in phase, adding 3 dB extra in sound level. Instead of using the positions of the grid in figure 1b, a source-receiver (S-R) pair was considered in the center of the orchestra. The S-R distance was increased by moving S and R outwards over the center line between position 1 to 10.

2.5. Room dimensions

Seven different rooms have been used for the investigation, each having different room dimensions and different locations of sound absorbing or diffusing materials. Table I shows an overview of the room dimensions. For the non-rectangular rooms, a range of dimensions is given, indicated by a ‘/’. Room MK was measured twice: once with a 1.5 m high screen in front of the percussion (position S1/R1), denoted ‘MKs’ and once without the screen, denoted ‘MKn’.

<table>
<thead>
<tr>
<th>Room</th>
<th>w [m]</th>
<th>d [m]</th>
<th>h [m]</th>
<th>F [m^2]</th>
<th>V [m^3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK</td>
<td>14.5</td>
<td>11.5</td>
<td>4</td>
<td>165</td>
<td>650</td>
</tr>
<tr>
<td>ML</td>
<td>12.5</td>
<td>18</td>
<td>4</td>
<td>225</td>
<td>900</td>
</tr>
<tr>
<td>BM</td>
<td>12</td>
<td>30</td>
<td>3.6</td>
<td>360</td>
<td>1920</td>
</tr>
<tr>
<td>HZ</td>
<td>11.5/16.5</td>
<td>29</td>
<td>5.5/5.9</td>
<td>400</td>
<td>2250</td>
</tr>
<tr>
<td>MK</td>
<td>14</td>
<td>29</td>
<td>6</td>
<td>350</td>
<td>2400</td>
</tr>
<tr>
<td>BZ</td>
<td>15/20.5</td>
<td>24</td>
<td>2.1/7</td>
<td>430</td>
<td>2500</td>
</tr>
<tr>
<td>HB</td>
<td>13.8</td>
<td>26.5</td>
<td>8.9</td>
<td>380</td>
<td>3000</td>
</tr>
</tbody>
</table>

The material properties used for the ISM are given in Table II. Note that, in case the sound absorbing material on the wall is above 1.5 m, the low absorption coefficient is used of the reflective part of the wall in the ISM. The floor is fully reflective (a thin carpet in some of the rooms was neglected). The shape and material properties of the different rooms are further illustrated in figure 2. In the centre column, a 3D figure of each room is presented and material properties are indicated. The position of the measurement grid is illustrated using a red rectangle and figures are oriented in such a way that the conductors position is in the southwest.

<table>
<thead>
<tr>
<th>Room</th>
<th>F</th>
<th>B</th>
<th>L</th>
<th>R</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.05</td>
</tr>
<tr>
<td>ML</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.50</td>
</tr>
<tr>
<td>BM</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>HZ</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>MK</td>
<td>0.05</td>
<td>0.20</td>
<td>0.40</td>
<td>0.40</td>
<td>0.10</td>
</tr>
<tr>
<td>BZ</td>
<td>0.30</td>
<td>0.70</td>
<td>0.05</td>
<td>0.05</td>
<td>0.25</td>
</tr>
<tr>
<td>HB</td>
<td>0.30</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.90</td>
</tr>
</tbody>
</table>
BK is a 650 m² temporary rehearsal room. It has a reflective ceiling at 4 meters and 20 concave reflectors at 3 meter height. Sound absorbing panels made out of perforated board are attached to 25% of the sidewalls surface.

The ST in BK is high due to the 1st order ceiling and 2nd order ceiling to floor and wall to wall reflections. The steep trend in ST is well predicted but 2 dB lower as measured.

ML is a 900 m² typical rehearsal room that is also used as a community center. It has a lowered ceiling with absorptive and reflective tiles at 4 meters height and reflective walls.

The ST is lower than in room BK having the same ceiling height but now partly absorbing. The trend in ST is well predicted. The four outliers are results for position R10 at 1.9 m height above the middle of the room.

BM is a 1,920 m² multifunctional hall with a 100 m² stage with zigzag shaped stage walls. The walls and ceiling in the hall are covered with open laths (moderately sound absorbing). The stage is a 450 m² box opened to the hall.

The ST is relatively high due to the small stage volume. The trend in ST is well predicted above 4 m S-R distance. The outliers are results for position R10 (outside the stage).

HZ is a 2,250 m² multifunctional hall with a stage. The orchestra prefers to rehearse in the lower section of the hall, having a reflective ceiling at 5.5 m which is diffusive. The walls are reflective at ear level and absorptive above.

The ST is almost equal to room ML. The predictions show that the energy reflected by the 5.5 m reflective ceiling is comparable to the 4.0 m ceiling which is 50% absorbing.

MK is a 2,400 m² rehearsal room in a large industrial hall. Sound absorbing panels have been applied to the side walls (50% porous and 50% resonant) and are hung from the ceiling. A 1.5 m high removable screen can be put at the back of the orchestra to shield the percussion.

The ST is about -12 dB which is within the preferred range. Adding the screen results in a 0.5 dB increase, which is also predicted well.

BZ is a 2,500 m² auditorium with inclined seating area. The orchestra prefers to rehearse in the middle of the room. The back wall is sound absorbing, while the ceiling is egg-shaped with reflective and scattering panels.

The ST is about -11 dB which is within the preferred range. Similar to MK, in BZ the reflected sound level is equally dependant on the ceiling and side wall reflections.

HB is a 3,000 m² multifunctional auditorium with inclining seating area. The lower parts of the side walls and the full back wall are reflective, while the full ceiling and upper side-walls are highly sound absorbing.

The ST is about -14 dB which is just below the preferred range. The predictions show that, even though the T is only 0.7 s, the walls provide the early reflected sound energy.

Figure 2: Measured and predicted results for 7 rehearsal rooms.
3. Results

For each room, the results for the measurements are presented in figure 2. Per room, the graph on the left illustrates the ST_{early,d} as a function of distance for the indivudual S-R positions (dots show the 5 rotation average) and a logarithmic trend line is shown over all measurement S-R combinations (black line). The ISM prediction results for ST_{early,d} are presented as a red dashed line. Besides that, the position averaged ST_{early,d}, ST_{late} and the reverberation time T_{30} (500 and 1000 Hz average) are presented. The results for each room are briefly discussed in the text on the right side of figure 2.

In general, results for ST_{early,d} show that (much) more early reflected sound energy is present in most of these rehearsal rooms compared to concert hall stages. A similar increase was found for measurements in the covered part of orchestra pits, however, even the smallest rehearsal room still has a lower ST_{early,d} than the covered part of the orchestra pit. In most rooms, there is a moderate decay of ST_{early,d} over distance, which results in an equal distribution of early sound energy over the orchestra. Additionally, the ST_{late} shows that the amount of late reflected sound energy is similar to that on concert hall stages, even though the reverberation time is lower.

The ISM prediction results also show a moderate decay in ST_{early,d} over distance, but, the decay over distance does not appear to be logarithmic but almost straight (sometimes even slightly bell shaped). Looking further into details, the ISM calculations reveal that the reduction of sound level due to sound absorption is less than one might expect. For instance, the sound absorbing ceiling with \( \alpha = 0.5 \) in room ML, only reduces the 1st and 2nd order ceiling reflections by 3 dB. This amount of reduction is achieved when almost doubling the source to ceiling distance. This explains why the ST_{early,d} of room ML and HZ is very similar, even though the room volume is almost 2.5 times larger.

3.1 Room volume or stage volume?

This leads us to the question: what is the importance of room dimensions and room volume? In figure 3, the ST_{early,d} is presented as a function of room volume using blue diamonds. For the larger spaces above 1,500 m³, there appears to be a clear trend. However, the smaller rooms, BK and ML, appear to be exceptions. Based on the ISM predictions we can conclude that the surfaces nearest to the orchestra determine the value of ST_{early,d}, which is often the ceiling and side walls. Therefore, it might be more appropriate to consider the ‘stage volume’ instead of the room volume. In figure 3, the ST_{early,d} is also presented as a function of ‘stage volume’ using red dots, where the depth of the stage is either the actual stage depth (like BK and BM), or a maximum depth of 11 meters. Now, a trend can be observed for all measured rooms. However, it appears that, for a 900 m³ stage volume, the dimensions, presence of a backwall and the material properties can still make a difference up to 3 dB in ST_{early,d}.

The graph in figure 3 shows that, even with a larger room volume, the ST_{early,d} can be very high due to a small stage volume (for instance room BM with a 1,920 m³ room volume and a 500 m³ stage volume, see figure 2).

![Figure 3: ST_{early,d} as a function of room volume (blue) and ‘stage volume’ (red)](image)

![Figure 4: ST_{late} as a function of the total sound absorption, measured (blue) and predicted (red)](image)
Other room acoustic parameters have been investigated. In figure 4, the Late Support $ST_{\text{late}}$ is presented as a function of the total amount of sound absorption $A$, derived from $V$ and $T_{30}$ using Sabine’s equation ($A = 0.161 \frac{T}{V}$). Besides, Barron’s revised theory$^8$ is used to predict $ST_{\text{late}}$ ($10\log \left(\frac{312T}{V}\right) - \frac{6}{T}$) from an exponential decay. It is shown that, in 6 out 7 cases, $ST_{\text{late}}$ is predicted within 1.5 dB error (the single outlier is room ML. No reason has been found for this larger error). It is clear that a strong relation exist between the amount of sound absorption and the amount of late reflected sound energy.

### 3.2 Sound exposure

Especially the higher level of early reflected sound in rehearsal rooms, for all possible source to receiver distances, will contribute more to the total sound exposure of the musicians than on concert hall stages. The contribution of late sound to the sound exposure is expected to be in the same order of magnitude.

### 4. Discussion

#### 4.1 The stage design

Stage acoustic parameters have been studied for 7 different halls, used as rehearsal rooms and performance halls by wind orchestras. Both measurements and predictions were used to investigate the impact of sound absorption and room dimensions. In general, the Early Support over distance, $ST_{\text{early, d}}$, could be predicted within 2 dB error using the Image Source Method and 1$^{\text{st}}$ and 2$^{\text{nd}}$ order reflection only. This shows that the $ST_{\text{early, d}}$ is highly dependant on discrete sound reflections, of which its sound level depends on the distance between the sound source or receiver to the room surfaces and, to some extend, the surface properties like sound absorption and diffusion. The results suggest, that, with a stage volume of 900 m$^3$ a $ST_{\text{early, d}}$ can be achieved between -13 and -11 dB, which is mentioned by Gade as a possible optimal range.

#### 4.2 The room design

With a good ‘stage design’ as a starting point, the rest of the room could be designed to achieve appropriate late reverberation. Now, an assumption is made that a good orchestra surrounding can be designed in any room with a room volume higher than the appropriate ‘stage volume’ (this may lead to a ‘room in a room’ design). With Reverberation Time and Late Support available as design parameters, and the room volume possibly being dependant on other room requirements, one could look for an optimal balance between reverberation and ‘late loudness’. Figure 5 shows the $ST_{\text{late}}$ as a function of room volume for various reverberation times, based on Barron’s revised theory.

From this graph, the reverberation time can be determined that might fit the available room volume to achieve both a desired $ST_{\text{early}}$ and $ST_{\text{late}}$.

### Table II: optimal reverberation time for rehearsal rooms based on the room volume and a $ST_{\text{late}} = -14$ dB.

<table>
<thead>
<tr>
<th>$V_{\text{room}}$ [m$^3$]</th>
<th>1,000</th>
<th>2,000</th>
<th>3,000</th>
<th>4,000</th>
<th>5,000</th>
<th>6,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>0.75</td>
<td>1</td>
<td>1.25</td>
<td>1.35</td>
<td>1.5</td>
<td>1.75</td>
</tr>
</tbody>
</table>

It is clear that a room volume below 2,000 m$^3$ is not a good choice for a orchestra rehearsal room, as reverberation must be low to avoid being too loud. For a wind orchestra rehearsal room, a moderate reverberation might be desired, possibly with a maximum of 1.35 seconds. This asks for a 4,000 m$^3$ rehearsal room to avoid the room being too loud. For a symphony orchestra, that may desire more reverberation, possibly up to 1.75 seconds, a 6,000 m$^3$ volume would be needed. It is clear that the 7 measured rehearsal rooms do not fulfill any of such requirements. It should be noted all results in the research have been determined for rooms without the absorption and diffusion of the orchestra members on stage. In the near future, more research will be performed to investigate this particular topic.

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