# HOW A FULL SCALE ORCHESTRA OF DUMMIES ATTENUATES DIRECT AND REFLECTED SOUND

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## 1 INTRODUCTION

In concert hall and theatre design, it is important to consider the acoustics as perceived by the performers as well as the audience. Much research in the field of stage acoustics has focused on trying to define physical measures that could be used to predict musicians' perception of the acoustics. Some physical measures, namely the Early and Late Support parameters were introduced by Gade[1] and modified to $ST_{early,d}$ and $ST_{late,d}$ by Wenmaekers et al..[2] These parameters can be derived from a measured or calculated impulse response and have been used to model sound levels in orchestras.[3] Other suggestions for parameters are the Early and Late Sound Strength $G_{early}$ and $G_{late}$ as introduced by Dammerud et al..[4] All these parameters aim to measure the amount of sound energy reflected by the stage boundaries (i.e. early) and the hall boundaries (i.e. late). However, there is still a lack of agreement on what stage designs are preferred by musicians and what physical measures are of importance.[5] Studies using questionnaires with orchestra members judging concert halls did not always reveal a correlation between questionnaire results and physical measures.[5] One possible cause for a lack of correlation might be related to uncertainties in the physical measurement, when excluding the effect of blocking, absorption and scattering by orchestra members on the parameter values.

Dammerud and Barron[6] investigated the influence of orchestra members on the direct sound transfer in a hemi-anechoic scale model. Results showed a significant attenuation of the sound in the 0-50 ms time interval in the 1 and 2 kHz octave band, which increases by the distance between source and receiver. In the lower frequency bands up to 500 Hz, no attenuation was observed. These findings confirmed the results of earlier small scale experiments by Krokstad et al.[7] and Skålevik.[8] The sound path through the orchestra is not the only sound path affected by orchestra members. Further scale model and computer model studies by Dammerud[9] indicate that reflected sound levels in a hall are significantly influenced by the presence of the orchestra on stage. Results are based on four different stage enclosures in a generic concert hall shape, each tested both unoccupied and occupied by an orchestra consisting of 95 objects. Dammerud concluded that measures that involve late reflected sound ($ST_{late}$, $G_{late}$ and $T$) and, to some extent, measures taken at 1 meter source to receiver distance ($ST_{early}$ and $C_{80}$) are influenced by the orchestra consistently for each stage enclosure. However, measures that are taken with varying source to receiver distances and involving early reflected sound ($EDT$, $G_{early}$, $G_{7\text{-}50}$) did not show consistent variation.

To the best of our knowledge, no study has investigated the effect of orchestra members on the sound energy reflected from room boundaries on real scale. The goal of this paper is to better understand the effect of orchestra members, when present on stage, on the amount of early and late reflected sound. This effect has been quantified using the stage acoustic parameters Early and Late Support measured over distance, $ST_{early,d}$ and $ST_{late,d}$. Measurements have been performed on various stages and in orchestra pits under unoccupied conditions on an empty stage, a stage with stands and chairs, and with a full scale orchestra on stage. The orchestra has been simulated by using dressed mannequins. In this paper, only results are presented for the concert hall stage. All results will later be published in a journal paper.

# 2 METHODS AND VALIDATION

In this section, a description of the concert hall is given together with source and receiver positions. The measurement setup is documented, and the used acoustic parameters are explained. In addition, results from two validation studies on sound absorption and sound attenuation of the mannequins are presented.

## 2.1 Measurement conditions

Acoustic measurements were performed on a concert hall stage with the mannequin orchestra on stage, see Fig. 1. The loudspeaker and microphone positions are marked by black squares with numbers. The dimensions of the source and receiver grid are equal to the grid presented in Wenmaekers et al.[2] All positions on the left side of the stage and the middle position in the back are both source and receiver positions while all positions on the right side and at the conductor position are only receiver positions. Complementary to the positions shown in Fig. 1, a receiver position at 1 meter distance was used at each source position placed behind the source in a line towards the conductor position. Measurements were performed under three different conditions: (1) empty stage, (2) stage with chairs and stands and (3) stage with chairs, stands and orchestra members (mannequins). On the concert hall stage, theatre stage and in the opera house pit, an 80-piece mannequin orchestra was present.

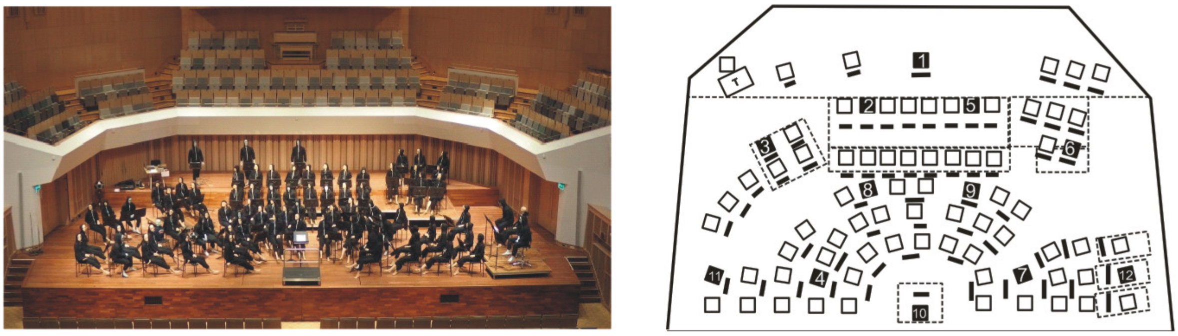

Fig. 1. Measurement setup with the mannequin orchestra on stage (left) and positions (right).

## 2.2 Measurement setup

Impulse responses were measured using an omnidirectional sound source, omnidirectional microphones. The transducer height was 1 m. Under occupied conditions, the chair and/or mannequin was removed from the position of the sound source and microphone. Normally, it is recommended to remove objects in a radius of 2 meters around the transducers when performing stage acoustic measurements and keep at least 4 meter distance from side walls with a 20 ms interval start, or in case of the orchestra pit also from the ceiling.[10] This is important to be able to accurately window out the direct sound without interference of the early reflected sound and vice versa. However, during the first set of measurements, it was found that removing objects from a 2 meter radius around both a single source and receiver position resulted in almost half of the orchestra being removed from the stage. It is clear that this would limit the possibilities of the measurements. Therefore, it was decided not to remove any objects during measurements. The uncertainty related to this problem is discussed in subsection 3.2.

## 2.3 Stage acoustic parameters

To evaluate the amount of early reflected sound energy, the Early and Late Support parameters are used as introduced by Gade[1] and modified by Wenmaekers et al.[2]:

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

$ST_{early;d}$ and $ST_{late;d}$ are the Early and Late Support at distance $d$, $p$ is the sound pressure measured at distance $d$, $p_{1m}$ is the sound pressure measured at 1 m distance and delay is the SR-distance divided by the speed of sound. Unless mentioned otherwise, the average over the 250 to 2000 Hz octave bands is used as a single number rating. The limit of the integration interval for useful reflections is reduced according to the time it takes for the direct sound to reach the receiver; see Wenmaekers et al.[2] for more background information. The reference sound pressure at 1 meter distance from the sound source was not determined in situ as suggested by ISO 3382-1.[11] Instead, a sound power measurement was performed in a reverberation room, as suggested by Gade.[10] More background information on the choice of sound power calibration can be found in a recent paper by the authors.[12]

## 2.4 Validation of the dummy orchestra

Kath[13] has shown that the sound absorption of people is mostly dependant on the clothing. Men wearing a suit absorb sound up to two times more than women wearing a summer dress. Persons in bathing suits absorb very little: less than 20% up to 2 kHz per person. To investigate the validity of using mannequins instead of humans for the experiments in the various halls, sound absorption measurements were performed. The mannequins were dressed with fleece jumpsuits. Figure 2 shows the measurement results for the configurations 1.0 m$^2$ per chair expressed as the total sound absorption $A_{sab}$ per person or chair as a function of frequency. In the third octave bands 400 to 5000 Hz a significant increase in sound absorption is observed when the chairs are occupied. For the condition with only men, the sound absorption of the mannequins is almost equal while the sound absorption of women is 18% lower on average for 400 to 5000 Hz. For the condition where men and women were mixed, measured in the 2 m$^2$ per chair setup, the sound absorption of the mannequins wearing jumpsuits is on average 9% higher in this frequency region. The difference in men and women explains the 9% deviation from the mannequins in the mixed group measurements.


Fig 2. Results of sound absorption measurements in the reverberation room.

## 2.5 Validation of sound attenuation

In addition to sound absorption, the attenuation of sound passing through a group of mannequins was investigated. Diagrams of the setup and results are shown in Fig. 3. A configuration of 1 $m^2$ per chair was made in a checkerboard pattern. Source and receiver positions were chosen such that different types of sound paths could be investigated: front to back (FB), left to right (LR), and diagonal (DIA). Some paths are blocked by chairs and other paths are unobscured. From measured impulse responses, the Sound Strength for the interval 0 up to 20 ms, $G_{0\text{-}20}$, was calculated. No side wall or ceiling reflections are included in this interval. To study the attenuation of the direct sound by humans or mannequins on chairs, the difference in $G_{0\text{-}20}$ is calculated between the empty condition and the condition with (occupied) chairs.

Figure 3 shows the sound attenuation for configuration 1 $m^2$ per chair occupied by humans and mannequins. In each graph, the sound level difference between the empty floor and occupied floor is shown for each type of sound paths. For a dense group of 1 $m^2$ per occupied chair, little variance is observed between different sound paths and attenuation tends to increase with frequency with a dip at 1000 Hz. Sound paths with an open sightline show similar attenuation to blocked sightlines. For the more spacious grouping of 2 $m^2$ per occupied chair, somewhat larger differences are shown between sound paths. In general, more attenuation occurs when the chairs are occupied by mannequins instead of humans. The average absolute difference for the 500 to 4000 Hz octave bands is 1.1 dB for the 1 $m^2$ per chair configuration and 0.9 dB for the 2 $m^2$ per chair configuration. Possibly, this difference is caused by the reference group of humans consisting of a 50/50 mix of men and women having lower sound absorption properties than the mannequins.

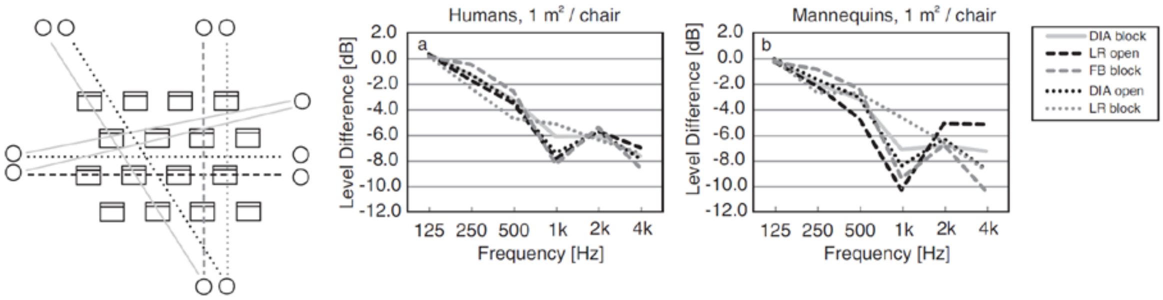


Fig. 3. Measurement setup (left) and results of sound propagation measurements in the sports halls with 1 $m^2$ per chair (middle figure for humans and right figure for mannequins).

## 2.6 Validation conclusion

We can conclude that the mannequins with fleece jumpsuits, either male of female shaped, correspond best to a male human: the sound absorption is equal and the attenuation of sound through a group of men most likely deviates less than 1 dB over 4 meters distance. The use of these mannequins instead of real humans can be seen as the scenario with most attenuation when judging their effect on stage acoustics, namely in case of a men-only orchestra.

# 3 RESULTS STAGE EXPERIMENTS

## 3.1 Direct sound attenuation

Sound passing directly through the orchestra is absorbed and scattered. In addition, the rigid floor reflects the sound upwards, resulting in destructive and constructive interference. It can be expected that most sound energy from the direct sound and floor reflection, denoted $L_{df}$, is measured within a time window of 10 ms after the actual direct sound arrival. Additionally, Dammerud and Barron[6] showed that ‘within orchestra reflections’ are visible in the impulse response at least up to 25 ms. The direct sound passing through the orchestra is denoted $L_{dfo}$. Figure 4 shows our results for $L_{df}$-$L_d$ and $L_{dfo}$-$L_d$ for each measured combination of source and receiver as a function of SR-distance for the octave bands 125 Hz to 4000 Hz. The direct sound, $L_d$, is determined from the sound power calibration in a reverberation room. A theoretical line is presented in the graphs that is based on the analytical model as used by Dammerud and Barron.[6]

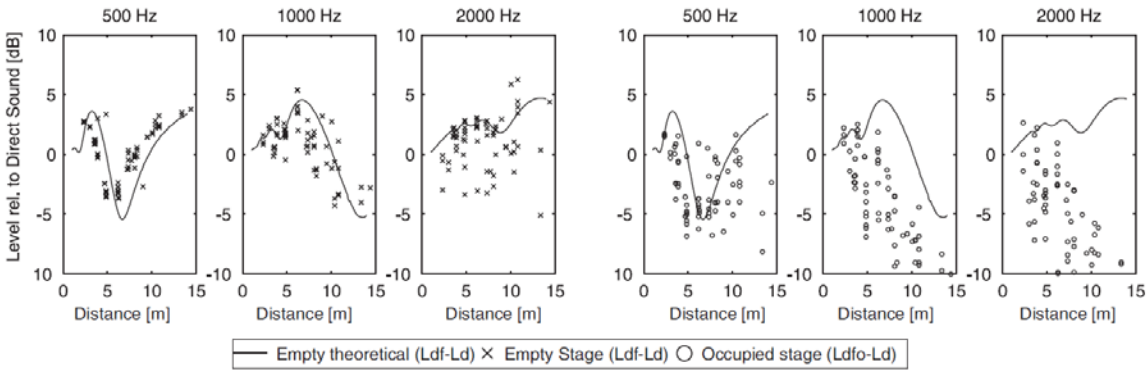


Fig. 4. Direct sound and floor reflection, relative to the direct sound, for the empty stage (left three graphs) and occupied stage (right three graphs) for octave bands 500, 1000 and 2000 Hz.

The interference of the direct sound by the floor reflection on the empty stage floor corresponds well with theory for the lower frequencies up until 500 Hz, although the theoretical line is shifted by approximately 1 meter (see Fig. 4 for the 500 Hz octave band result). From 1000 Hz, measured values show less constructive interference as expected from theory resulting in lower values for $L_{df}$. Random variation exists that can only partly be explained by the directivity of the sound source.[12]

The direct sound level is reduced at most positions when the stage is occupied by the chairs, stands and mannequins. Results of $L_{dfo}$ as a function of distance are more scattered. The consistent reduction shows that the reduction in sound level by absorption and scattering is larger than the increase of sound level by ‘within orchestra reflections’. We compared our results for the level of the sound passing through the orchestra, $L_{dfo}$, to the trend lines as suggested by Dammerud and Barron.[5] It can be concluded that, in the frequency bands 500, 1000 and 2000 Hz, $L_{dfo}$ is consistently lower in our study with an average deviation from their trend lines varying from 3 to 6 dB. For octave bands 1000 and 2000 Hz, it can be confirmed that $L_{dfo}$ reduces when the distance increases. However, the variation in our data is found to be too large to be able to significantly determine regression lines as a function of distance. Possibly, this is caused by the random direction of positions opposed to the line-measurements done by Dammerud and Barron.

## 3.2 Early reflected sound

The sound that reflects from the stage boundaries also passes through the orchestra. Especially for horizontal reflection paths, a reduction in reflected sound level can be expected. The amount of early reflected sound energy has been measured for three configurations: the empty floor, the floor filled with chairs and stands, and those chairs occupied by mannequins. The parameter used to measure the early reflected sound energy is the extended Early Support $ST_{early,d}$. The time window in this parameter starts at 10 ms after the direct sound arrival to be able to window out the direct sound and floor reflection. To avoid room reflections to arrive within this interval, no room reflections other than the floor reflection should arrive before 10 ms as they would be windowed out. Therefore, it is recommended to avoid having reflecting surfaces closer than 2 meters from any transducer. In our experiments, the objects like chairs, stands and mannequins had to be close to the transducers. It is important to investigate when reflections from these objects will mask the reflected sound energy coming from the stage boundaries. To find the lowest possible $ST_{early,d}$ that would be measured on an empty and occupied stage, we investigated $ST_{early,d}$ for the theatre stage without reflecting panels while keeping the curtains in place. At short source receiver distances of 1-3 m, the maximum value for $ST_{early,d}$ is -16 dB, with a 2 to 3 dB increase in the occupied condition compared to the empty stage. For 3-5 meters mutual distance, $ST_{early,d}$ was hardly effected by objects' reflections with a maximum value $ST_{early,d}$ = -18 dB. Beyond 5 meters, $ST_{early,d}$ was reduced by the objects on stage and a value of $ST_{early,d}$ = -20 dB was not exceeded in the empty condition. These maximum values are used as a threshold above which energy from room reflections can be considered to be stronger than the energy reflected from objects like chairs, stands or mannequins.

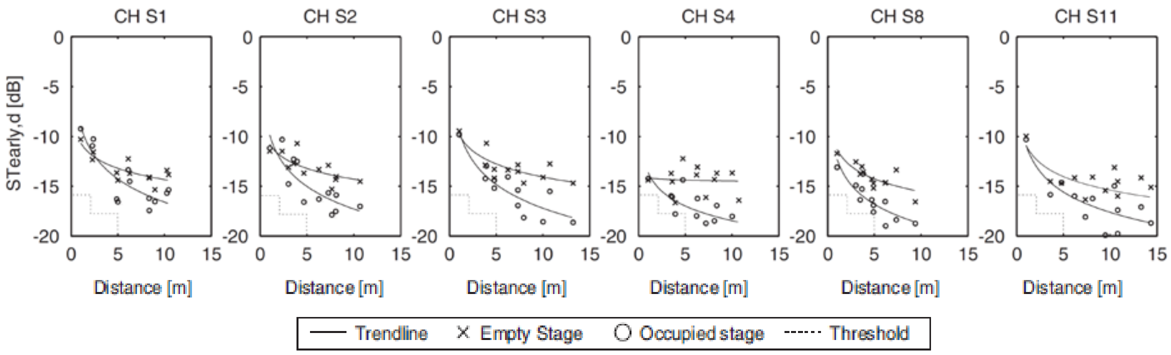


Fig. 5. Early reflected sound level, measured by $ST_{early,d}$ as a function of SR-distance for source positions S1, S2, S3, S4, S8 and S11 for the empty concert hall stage (marked 'x') and the concert hall (CH) stage occupied with the mannequin orchestra (marked 'o').

In Fig. 5, absolute results are presented for $ST_{early,d}$ as a function of SR-distance for the concert hall stage. Individual results are given for the empty and occupied condition with separate logarithmic trend lines. The threshold above which reflected energy from room boundaries is significant, is shown in dashed lines. The early reflected sound level, measured by $ST_{early,d}$, tends to decrease as a function of SR-distance for most source positions or source-receiver groups. Reflecting walls relatively close to the source position project the sound over the stage or pit causing $ST_{early,d}$ to decrease with SR-distance. For the source positions on the outside of the orchestra, S1, S2, S3 and S11, regression analysis shows a correlation with $R^2$ > 0.75 between SR-distance and the shortest first order reflection path length (reflecting most of the early energy). In can be expected that the amount of attenuation by the orchestra also increases when path lengths in the horizontal plane increase. For source positions close to walls this explains why the early reflected sound is more reduced by the orchestra when SR-distance increases.

However, when the sound source is located in the middle of the orchestra, like S4 and S8, reflection path calculations show that the shortest side wall reflection path length does not correlate well with SR-distance. Indeed, the $ST_{early,d}$ data at source position S4 show poor correlation with SR-distance. Surprisingly, $ST_{early,d}$ does correlate reasonably well with the SR-distance for S4 (and S8) when the orchestra is included in the measurement with $R^2$ = 0.50. At these typical positions, measured values of $ST_{early,d}$ are close to the threshold, which is the minimum value measured on a non-reflective stage. As shown before, at relatively low $ST_{early,d}$ values and short SR-distances up to 3 meters, measured $ST_{early,d}$ increases when the orchestra is present due to 'within orchestra reflections'. This is likely the reason why measured $ST_{early,d}$ decreases as a function of SR-distance at source positions in the middle of the orchestra, even when the reflection path lengths do not increase with SR-distance.

On the occupied stage, $ST_{early,d}$ shows a clear dependency with SR-distance in all source positions. At the concert hall stage, the difference in $ST_{early,d}$ at 1 and 10 meter distance is up to 8 dB. On one hand, the large variation of $ST_{early,d}$ over distance shows that judging the amount of early reflected sound on stage based on solely 1 meter distance measurements, limits the judgement of the stage's performance. On the other hand, it seems that $ST_{early,d}$ is the least influenced by the presence of the orchestra when measuring at the 1 meter SR-distance as suggested by ISO 3382-1.

## 3.3 Late reflected sound

As concluded in a previous study,[2] $ST_{late,d}$ did not show a relation with distance, both on the empty stage as well as the occupied stage. One might expect that the late arriving energy can be described as a diffuse sound field. Following Barron's revised theory[17], $ST_{late,d}$ can be predicted by the room volume $V$ and reverberation time $T$:

$$ST_{late,d} = 10\lg\frac{31200T}{V}e^{-(13.82\times 0.103/T)} - 20\,.$$

Alternatively, it can be written as:

$$ST_{late,d} = 10\lg(312T/V) - 6.2/T\,.$$

In previous research on rehearsal rooms[18] it was found that $ST_{late,d}$ could be predicted within 1.5 dB deviation for 6 out of 7 rehearsal rooms. For the concert hall, we investigated whether the difference in $ST_{late,d}$ could be explained by a measured 5% reduction in reverberation time for the 250-2000 Hz octave bands due to the absorption of the orchestra. For the empty condition, $ST_{late,d}$ is predicted using Barron's revised theory within 0.1 dB error, which confirms that the revised theory holds for the empty stage. However, based on the measured reduction in $T$, the addition of the chairs, stand and mannequins would only lead to -0.3 dB difference in $ST_{late,d}$, while the measured difference is -1.7 dB. The late reflected sound is reduced by the presence of the orchestra much more than Barrons' revised theory predicts. Even though the late reflected sound energy returns from the larger room volume, it seems that is absorbed locally near the sound source and receiver on stage.

# 4 CONCLUSION

The effect of absorption and scattering of sound by orchestra members on stage has been investigated by measurements on stages and in orchestra pits. In this paper, the measurement results for a single concert hall stage have been discussed. The orchestra was simulated by using dressed mannequins. Validation studies have shown that these mannequins have similar behaviour as male humans in terms of how much sound they absorb and how sound propagates through a group. Results of impulse response measurements show that direct sound, early reflected sound and late reflected sound are significantly affected by the orchestra compared to an empty stage or a stage with chairs and stands only. The difference is not systematic; it varies per source-receiver position, and as we will show in a upcoming journal paper, per stage or orchestra pit. Both the direct sound and early reflected sound levels (measured by $ST_{early,d}$) are reduced by the orchestra, increasingly as a function of source-receiver distance. The late reflected sound level, which is not dependant on source-receiver distance, is reduced considerably more than can be expected based on Barron's revised theory and reverberation time. It can be concluded that acoustic measurements on a stage without the orchestra being present, result in significant errors, especially when measurements are performed with source-receiver distances larger than 1 meter.

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