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Stage acoustic parameters aim to quantify the amount of sound energy reflected by the stage and hall boundaries and the energy decay over time. In this research, the effect of orchestra presence on parameter values is investigated. The orchestra is simulated by dressed mannequins, which have been compared with humans with respect to acoustic properties. Impulse response measurements were performed in a concert hall, a theatre, a rehearsal room, and in two orchestra pits. Conditions were empty stage floors, stage floors with music stands and chairs only, and floors occupied by the mannequin orchestra. Results show that the direct and reflected sound levels and the energy decay are significantly affected by the orchestra compared to an empty stage or a stage with chairs and stands only. Both the direct sound and early reflected sound levels are reduced by the orchestra with the distance. The late reflected sound level is reduced considerably more than can be expected based on Barron's revised theory. It can be concluded that measurements on a stage without the orchestra being present results in significant differences. A practical method is presented to perform a "musician friendly" stage acoustic measurement with a real orchestra.
© 2016 Acoustical Society of America. [http://dx.doi.org/10.1121/1.4971763]

I. INTRODUCTION

In concert hall and theatre design, it is important to consider the acoustics as perceived by the performers as well as by the audience. Much research in the field of stage acoustics has focused on defining physical parameters to predict musicians' perception of the acoustics. The early and late support parameters ST_{early} and ST_{late} were introduced by Gade[1] and modified to $ST_{early,d}$ and $ST_{late,d}$ by Wenmaekers *et al.*[2] These ST parameters measure the amount of sound energy arriving early and the sound energy arriving late on stage. Other suggestions for parameters are the early decay time (EDT), early ensemble level[1] (EEL), and the early sound strength,[3] or G_{early}. In these other parameters, the direct and early reflected sound energy are included. Extensive information on the various (other) parameters that have been used in stage acoustics can be found elsewhere.[2]

However, there is still a lack of agreement on what stage designs are preferred by musicians and what physical parameters are of importance.[5] Studies using questionnaires with orchestra members judging concert halls did not consistently reveal a correlation between perceptual attributes and physical parameters.[5] For instance, Dammerud *et al.*[3] conclude that acoustic parameters that measure early reflected sound on stage have poor subjective relevance while parameters judging late reflected sound can be significant predictors of musicians' preference. One of the various possible causes for a lack of correlation might be related to uncertainties in the physical measurement, for instance when excluding the effect of absorption and scattering by orchestra members on

the parameter values.[3] This is the subject of investigation in the current paper. It is often suggested that including source and receiver directivity might improve the subjective relevance of early reflected sound parameters.[3,4,6] In the current paper, this topic is considered to be important future research and only omnidirectional parameters are investigated.

Dammerud and Barron (in this paper denoted D&B) investigated the influence of orchestra members on the direct sound transfer in a hemi-anechoic scale model.[7] Results showed a significant attenuation of the sound in the 0–50 ms time interval for 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.*[8] and Skålevik.[9] Chairs, stands, and orchestra members do not only cause a direct sound attenuation. D&B also note that the energy in the impulse response smears out over time, and "within orchestra reflections" can also increase the level of sound in the orchestra.[7] This suggests that the direct sound attenuation by the orchestra members might be compensated by the orchestra reflections to some extent.

The direct sound path through the orchestra is not the only path affected by orchestra members. Further scale model and computer model studies by Dammerud[10] indicate that reflected sound levels in a hall are significantly influenced by the presence of the orchestra on stage. Results are based on different stage enclosures in a generic concert hall shape. Dammerud concluded that parameters that involve late reflected sound (ST_{late} and G_{late}) and, to some extent, parameters taken at 1 m source to receiver distance (ST_{early}) are moderately reduced by the orchestra. However,

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parameters that are taken with varying source to receiver distances and involving early reflected sound (G_{early}, G_{7-50}) showed considerable reductions. To the best of our knowledge, no study on real scale has investigated the effect of orchestra members on the sound propagation over a sound path where energy is reflected from room boundaries.

The goal of this paper is to better understand the effect of orchestra members, when present on stage, on the amount of direct, early, and late reflected sound. Measurements have been performed on five stages and orchestra pits in unoccupied conditions and with a full scale orchestra. The orchestra has been simulated by using dressed mannequins. In this paper, we show that the reduction in sound passing directly through the "real" orchestra is considerably higher than measured on scale by D&B.[7] The average reduction in early reflected sound level due to the orchestra members is small at short source to receiver distances (r), but the reduction increases considerably with increasing r. In Sec. II, the measurement methods are explained and the acoustic properties of mannequins are compared to those of humans. In Sec. III, results are presented from the stage acoustic measurements on the stages and in orchestra pits. The results are discussed in Sec. IV. In Sec. V, a practical example is presented of a measurement method that can be used to measure a stage occupied by a real orchestra.

II. METHODS

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

A. Halls and positions

Acoustic measurements were performed on a concert hall stage, a theatre stage, a rehearsal room stage, and in two orchestra pits. Figure 1 shows pictures of the different venues with the mannequin orchestra on stage or in the pit. On the concert hall stage, part of the orchestra members were positioned on risers. In case of the theatre stage, measurements were taken with and without the wooden reflective elements around the orchestra. Figure 2 shows schematic overviews of the positioning of chairs and loudspeaker and microphone positions. For the concert hall and theatre stage, the dimensions of the source and receiver grid are equal to the grid shown below in Fig. 2. For the orchestra pits and rehearsal room, the source–receiver grid was scaled so it would fit in the available space and positions would correspond to possible seating locations of musicians. Complementary to the positions shown in Fig. 2, a receiver position at 1 m distance was used at each source position placed behind the source in a line towards the conductor position (position 10).

B. Measurement conditions

Measurements were performed under three different conditions: (1) empty stage, (2) stage with chairs and stands,

Concert Hall stage (CH)

Theatre stage (TH)

Rehearsal room stage (RH)

Theatre Orchestra Pit (THop)

Opera House Orchestra Pit (OHop)

FIG. 1. (Color online) Concert hall stage of Muziekgebouw Eindhoven (CH); Theatre stage of Parktheater Eindhoven (TH); Stage of the wind orchestra rehearsal room MFC Berg aan de Maas (RH); Orchestra pit of theatre Parktheater Eindhoven (THop); Orchestra pit of opera house Nationale Opera and Ballet Amsterdam (OHop).

4438   J. Acoust. Soc. Am. **140** (6), December 2016

Wenmaekers *et al.*

Concert Hall stage (CH)

Theatre stage (TH)

Rehearsal room stage (RH)

Theatre Orchestra Pit (THop)

Opera House Orchestra Pit (OHop)

Measurement Grid

⊠ conductor 0.5m from stage edge
■ source and receiver position
▪ receiver position
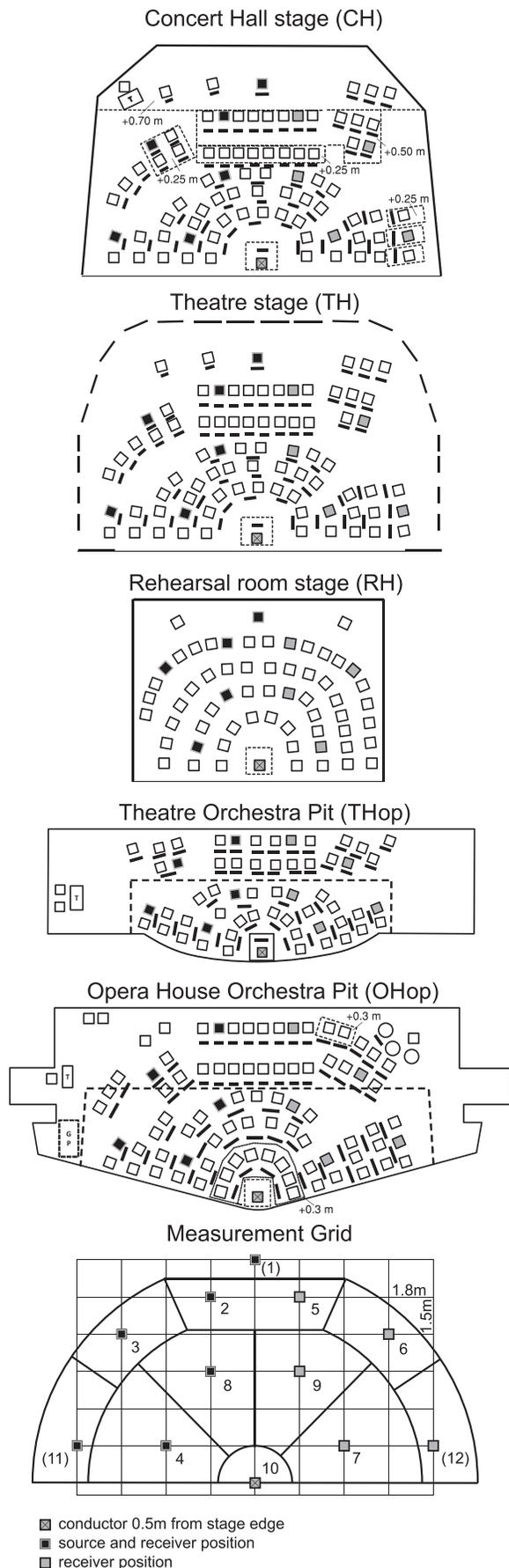
FIG. 2. Positions of chairs, stands and mannequins per room, together with a schematic representation of the measurement grid. Filled chairs: transducer positions.

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. In the theatre pit and wind orchestra rehearsal room, a 60-piece mannequin orchestra was present. Music stands were present in most halls, indicated by the short bold lines in the drawings in Fig. 2, with the exception of the rehearsal room where no stands were available.

C. Measurement setup

Impulse responses were measured using an omnidirectional sound source (B&K type 4292), a single omnidirectional microphone (B&K type 4189), an Amphion amplifier (AE) and measurement software Dirac 6.0 (B&K type 7841). The transducer height was 1 m. Although impulse response measurements from multiple rotations of the source would have been preferred to suppress source directivity effects that arise at higher frequencies, this was not possible due to time constraints, and a single measurement for every source–receiver combination was taken. A fixed source aiming point was used perpendicular to the stage edge. Using measurement data from a previous study on sound source calibration[11] we determined that, compared to a full rotational average with 72 measurements, the uncertainty (probability level of 95% using a coverage factor of 2.8) of a single impulse response (IR) measurement is

• 2.8 dB for the direct sound (0–10 ms), 1.2 dB for the early reflected sound (10–100 ms) and 0.4 dB for the late reflected sound (100–1000 ms) for the separate octave bands up to 2 kHz.
• 0.8 dB for the direct sound (0–10 ms), 0.3 dB for the early reflected sound (10–100 ms) and 0.1 dB for the late reflected sound (100–1000 ms) for the average of the octave bands 250 to 2000 Hz.

Gade recommends to remove objects in a radius of 2 m around the transducers when performing stage acoustic measurements and keep at least 4 m distance from side walls.[12] At first, this is important to be able to accurately window out the direct sound without interference of the early reflected sound, and to always include the earliest wall reflection in the measurement. Later on, Gade recommended to use the free field sound pressure at 1 m distance from the sound source as a reference,[12] which is different from the definition in ISO 3382-1.[13] Following Gade's recommendation, in current study a sound power measurement was performed in a reverberation room to determine the reference level by $L_{ref} = L_w - 11$ dB. Even now the reference level is not determined on stage, it would still be necessary to remove objects around transducers and keep a distance from the side wall to include all reflections within the early energy time window. However, during the first set of measurements in the rehearsal room, it was found that removing objects from a 2 m radius around both a source and receiver position resulted in too many orchestra members being removed from the stage. It is clear that this would limit the possible outcome of this study. Therefore, it was decided not to remove any objects during measurements apart from the chairs and/

or mannequins on the sound source position and on the microphone position. The uncertainty related to this problem is discussed in Sec. III B.

D. Stage acoustic parameters

Four different acoustic parameters were selected for the investigation: an early and late decay parameter, i.e., EDT and T_{20}, and an early and late sound level parameter, i.e., ST_{early} and ST_{late}.

The EDT measures the reverberation time over the 0 to -10 dB drop of the Schroeder curve, and T_{20} is determined over the -5 to -25 dB drop. Both EDT and T_{20} should be measured at distances larger than 1 m from the source.[1] While T_{20} ignores the influence of direct sound, the EDT is sensitive to the direct sound in the measurement, which can be strong close to the sound source. EDTF, the frequency ratio of EDT for 250 and 500 Hz relative to 1 and 2 kHz, was a promising predictor for the evaluation of *Timbre*.[1]

The early and late support parameters are used as introduced by Gade,[1] as well as those extended and modified by Wenmaekers *et al.*:[2]

$$ST_{early,d} = 10\lg\left(\frac{\int_{10}^{103-\text{delay}} p_d^2 dt}{\int_0^{10} p_{1m,\text{free-field}}^2 dt}\right), \quad (1)$$

$$ST_{late,d} = 10\lg\left(\frac{\int_{103-\text{delay}}^{\infty} p_d^2 dt}{\int_0^{10} p_{1m,\text{free-field}}^2 dt}\right), \quad (2)$$

where $ST_{early,d}$ and $ST_{late,d}$ are the early and late support at distance d, p is the sound pressure measured at distance d, $p_{1m,\text{free-field}}$ is the free field sound pressure measured at 1 m distance derived from a sound power measurement, and *delay* is distance r times 1000 divided by the speed of sound. Unless mentioned otherwise, the average ST over the 250 to 2000 Hz octave bands is used in this paper as a single number rating.

For measurements at 1 m distance, the parameter definitions of $ST_{early,d}$ and $ST_{late,d}$ are almost identical to the original ST_{early} and ST_{late}.[2] In $ST_{early,d}$ at 1 m the lower limit has changed from 20–100 ms to 10–100 ms. It was concluded[2] that this is necessary to include very early reflected sound and that this is possible without including the direct sound or floor reflection. This modification leads to differences (averaged over 10 concert hall stages) between $ST_{early,d}$ and ST_{early} ranging from only 0.3 dB at position S4 close to the stage edge up to 2.7 dB for position S1 often close to 2 m from the back wall.[2] Results for the original ST_{early} are also discussed in the current study. The difference between $ST_{late,d}$ and ST_{late} is negligible: only 0.02 dB from an average of 11 concert hall stages. This small difference is caused by the upper limit being changed from 100–1000 to 100–infinity, where infinity is defined as the crosspoint between impulse response decay and noise floor.

For measurements at distances above 1 m, the limit of the integration interval of $ST_{early,d}$ for useful reflections is reduced according to the time it takes for the direct sound to reach the receiver. This means that the interval is defined relative to the time of emission, similar to the concept of EEL. The direct sound is not included in $ST_{early,d}$, which is the main difference between $ST_{early,d}$ and EEL. The early reflected sound does not have a large contribution to the total level with the direct sound included, which is equal on all (empty) stages. As a result, $ST_{early,d}$ seems about twice as sensitive to differences between stages than EEL (or G_{early}). It was shown for measurements on empty stages,[2] that when using a fixed source and receiver grid on different stages, differences in measured values of EEL in eight concert halls are small, varying by only 4 dB at 10 m distance, while $ST_{early,d}$ differed up to 9 dB per hall at this distance.

As Gade concludes in his recent paper,[5] there is still no agreement on which time limit is most appropriate for the ratio between early and late sound on stage. For comparing early reflected sound levels on different stages, the exact choice of time limit is not that relevant. In an earlier paper,[2] it was shown that different time windows on either early or late reflected sound would not lead to a difference in ranking of eight different halls. Therefore, the extended and modified versions of the well-established ST parameters were a logical step and are considered being most appropriate for current research.

Dammerud *et al.*[3] suggested that parameters based on the definition of Sound Strength can be more reliable because of the laboratory calibration procedure. However, according to Gade,[12] the sound source should also be calibrated in the laboratory for measuring ST parameters using the reverberation room method, instead of measuring *in situ* as suggested in the ISO3382-1 standard.[13] This means that the stage acoustic parameters based on G, like G_{early} and G_{7-50}, only differ from ST in the choice of time window. Because G_{early} includes direct sound, it is less sensitive to variations in stage design than $ST_{early,d}$ and therefore less suitable. G_{7-50} uses a time window that starts at 7 ms instead of 10 ms, and therefore includes the floor reflection at short distances, which is regarded to belong to the "direct sound" as well. The choice for a 50 ms upper level is not explained by Dammerud *et al.*[3] Because of the limited proven validity of the G parameters, they were not included in current study.

E. Impulse response quality

All measurements presented in Sec. III had a decay range or impulse response to noise ratio (INR) > 40 dB for the separate 250 to 2000 Hz octave bands. For an accurate calculation of ST_{early} and ST_{late} parameters at 1 m distance (error ≤ 0.2 dB), the decay range INR of the impulse response should be at least 28 and 39 dB, respectively.[14] It is assumed that the requirement for G is valid for $ST_{early,d}$ and $ST_{late,d}$ at further distances, which is an INR ≥ 28 dB for an error ≤ 0.1 dB (the higher requirement at 1 m distance is caused by the strong direct sound peak in such a measurement which increases the INR). With the achieved decay range INR > 40 dB, the reverberation time parameters EDT

and T_{20} can be determined with errors ≤ 0.2 JND and ≤ 0.7 JND, respectively (equivalent to 1% and 4%) with JND being the just noticeable difference.

F. Comparison of sound absorption

Kath[15] 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, and persons in bathing suits absorb very little: an absorption coefficient less than 0.2 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. Eight male participants wore normal clothing with long trousers and a thin jacket. Eight female participants wore normal clothing with arms and legs covered. The participants sat on chairs with a foam back and foam seating, which are similar to chairs that are normally used by an orchestra. Mannequins were chosen to be made out of fibre glass (9 kg per mannequin) because they absorb little sound, similar to humans without clothes. For clothing, fleece jumpsuits (3 mm thick, 200 g/m^2) with long sleeves were chosen with a hood to simulate hair. The sound absorption measurement was performed in a 90 m^3 reverberation room with an 8 m^2 surface area surrounded by a wooden perimeter following ISO 354.[16] Even though it is recommended to use a larger room volume and sample size, for the sake of comparing objects this setup was judged sufficient. Two configurations were tested with varying area per seat: 1 and 2 m^2 per chair; see Fig. 3. The configuration with 1 m^2 per chair was tested with male and female participants separately, see Fig. 4 for an example of the setup. A configuration with 2 m^2 per chair was tested with a mix of 50% men and 50% women.

Figure 5 shows the measurement results expressed as the total sound absorption A per person or chair as a function of frequency. In the third octave bands 400–5000 Hz a significant increase in sound absorption is observed when the chairs are occupied. Compared to real men only, the sound absorption of the mannequins is almost equal while the sound absorption of real women is 18% lower on average for the third octave bands 400–5000 Hz. This can be explained by the fact that the women were smaller than the men and wore thinner/less clothing. Compared to the mixed compositions of men and women, the sound absorption of mannequins wearing jumpsuits is on average 9% higher in this frequency range.

Because the jumpsuits turned out to be indispensable for handling and protecting the mannequins during measurements and transport, it was decided not to reduce the
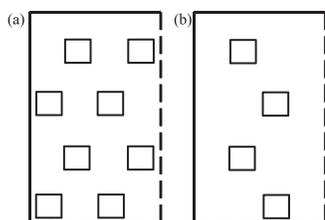
FIG. 4. (Color online) Sound absorption measurement setup in the reverberation room with 1 m^2 per chair occupied by eight women.

clothing for the mannequins that were to simulate female orchestra members. Figure 5 also shows reference values for sound absorption per orchestra member found in literature[7,17] and *in situ* values based on our measurement in the concert hall. Differences per octave band exist with a maximum of 0.25 and the measured absorption of the dressed mannequins averaged over all octave bands is 0.12 larger than the average value of all references. The latter agrees with our mannequins having a larger sound absorption than real men and women mixed by 0.09. However, the absolute absorption values should be interpreted with care because the volume of the measurement room does not meet the volume of the standards.

G. Comparison of sound propagation attenuation

In addition to sound absorption, the attenuation of sound passing through a group of mannequins (without music stands) was investigated. A picture of the experimental setup in a sports hall is shown in Fig. 6 and diagrams of the setup are shown in Fig. 7. Two configurations of 1 and 2 m^2 per chair were made in a checkerboard pattern. Different types of sound paths have been investigated: front to back (FB),
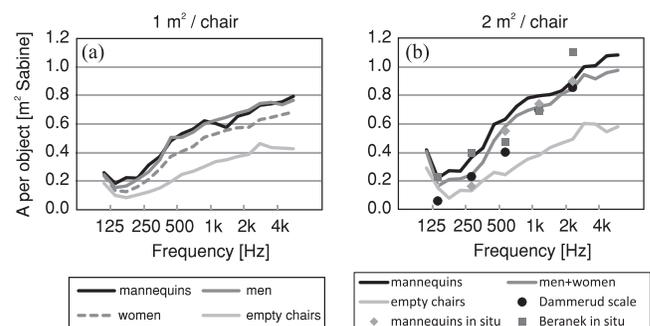
FIG. 5. The total sound absorption per empty chair, per chair with mannequins and per chair with individuals for two configurations: Left: 1 m^2 per chair; right: 2 m^2 per chair. The right graph shows reference values for sound absorption per orchestra member found in literature (Refs. 7 and 17) and *in situ* values based on our measurement on the concert hall stage with and without the mannequin orchestra (using Sabine's equation).

FIG. 3. Sound absorption measurement setup in the reverberation room: (a) 1.0 m^2 per chair with 8 chairs; (b) 2.0 m^2 per chair with four chairs.

J. Acoust. Soc. Am. **140** (6), December 2016

Wenmaekers *et al.* 4441

FIG. 6. (Color online) The attenuation of direct sound through a group of humans and a group of mannequins has been measured in a sports hall for validation. The picture shows the setup with the group of mannequins.

FIG. 8. The level difference between the direct sound measured with an empty floor and the direct sound measured (a) 1 m² per human on chair, (b) 1 m² per mannequin on chair, (c) 2 m² per human on chair, and (d) 2 m² per mannequin on chair.

left to right (LR), and diagonal (DIA). While some paths are blocked by chairs, other paths are unobstructed. Impulse response measurements have been performed while rotating the sound source in steps of 72 deg. To study the attenuation of the direct sound by humans or mannequins on chairs, the difference in G_{0-20} is calculated between the empty floor condition and the condition with occupied chairs.

Figure 8 shows the sound attenuation for chairs occupied by humans (men and women) and mannequins. For a dense group of 1 m² per occupied chair, little variation is observed between different sound paths and attenuation tends to increase with frequency with a dip at 1000 Hz. This dip is caused by the highest constructive interference for 1000 Hz by the floor reflection at 6 m distance in the empty floor case, which is attenuated by the objects. Sound paths with an open line of sight show similar attenuation to blocked lines of sights.

For the more spacious grouping of 2 m² per occupied chair, larger differences are shown between sound paths. Surprisingly, only the open sound path going from front to back stands out for being different, even showing a slight increase in sound level, while the open sound path going from left to right is more similar to other sound paths.

In general, more attenuation occurs when the chairs are occupied by mannequins instead of humans. For the 1 and 2 m² per chair configuration, the average absolute difference for the 500–4000 Hz octave bands is 1.1 and 0.9 dB, respectively. Possibly, this difference is caused by the reference group of humans consisting of a mix of 50% men and 50% women having lower sound absorption properties than the mannequins as reported above.

H. Comparison conclusion

We can conclude that the mannequins with fleece jumpsuits are a sufficiently accurate substitute for real male humans: their sound absorption is almost equal to real men and the attenuation of sound, averaged over various directions over 6 m distance through a group of mannequins, deviates equal to or less than 1.1 dB from real men. The use of these mannequins instead of real humans can be seen as the scenario with most attenuation: in case of a men-only orchestra. If a mannequin orchestra is needed to be reproduced for experiments, it is likely that similar rigid plastic mannequins with orchestra-like clothing will have proper absorption and sound propagation attenuation. If normal clothing can be used instead of jumpsuits, it would be possible to discriminate between men and women having different absorption properties. However, it is recommended to check the sound absorption in a reverberation room.

III. RESULTS STAGE EXPERIMENTS

In this section, results are presented obtained from the experiments performed on the stages and in the orchestra pits. First, the direct sound attenuation will be presented. After that, the results for the stage acoustic parameters are presented. Note that the discussion of the results is found in Sec. IV.

FIG. 7. Measurement positions and location of seats for the sound attenuation validation study. Source–receiver distance 6–7 m. Left: 1 m² per chair. Right: 2 m² per chair.

A. Direct sound results

It can be expected that most sound energy from the direct sound and floor reflection is captured within a time window of 10 ms after the actual direct sound arrival. Additionally, D&B[7] showed that within orchestra reflections are visible in the impulse response at least up to 25 ms. The direct sound is denoted L_d, the direct sound including floor reflection is denoted L_{df} and the direct sound including floor reflection passing through the orchestra is denoted L_{dfo}. Impulse responses were measured on the full scale theatre stage without the wooden reflective elements as visible in Fig. 1, but with stage curtains hung at 2.8 m distance from the nearest transducer position. Due to the curtain reflections, we can only investigate L_{dfo} for the time window 0–16 ms. The original impulse responses measured in the scale model study by D&B[18] have been re-analysed for these time windows. The difference between the sound level within the 0–25 ms and the 0–16 ms interval of only $0.3 +/- 0.2$ dB found is negligible. This means that our data can be compared to the data presented in D&B.[18]

Figure 9 shows our results for L_{df}-L_d and L_{dfo}-L_d for each measured combination of source and receiver on the theatre stage as a function of r for the octave bands 125–4000 Hz. The direct sound L_d is derived from the sound power measurement in the reverberation room by $L_d = L_w - 10 \lg(4\pi r^2)$. A line is presented in the graphs as well that is based on the analytical empty stage model for L_{df}-L_d as used by D&B.[7]

The variation for L_{dfo}-L_d can partly be explained by the "object density" in the direct sound path. The lowest sound reduction is found in the areas that are more open, typically

positions on the same side at the edge of the orchestra (Edge). An average amount of reduction is found for sound paths that run diagonally or sideways (Diag/Side). The largest sound reduction is found for paths going from the front to back in the middle section (Front–Back). The results for L_{dfo}-L_d are presented in Fig. 10 together with one trend line that corresponds with our data and one based on D&B,[6] Table II. Our sound paths along the edge are plotted together with their trend line B, which was a line without obstructions. The diagonal and sideways sound paths are compared to their trend line A and the front-back sound paths to their trend line C.

B. Early reflected sound threshold

To obtain threshold values at above which energy from room reflections can be considered to be stronger than the energy reflected from objects on stage, we investigated $ST_{early,d}$ for the theatre stage without wooden reflecting elements. At short source–receiver distances of 1–3 m, the maximum value for $ST_{early,d}$ is -16 dB, with a 2–3 dB increase in the occupied condition compared to the empty stage. For 3–5 m distance, $ST_{early,d}$ was hardly affected 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.

C. Early sound results

In Fig. 11, absolute results are presented for $ST_{early,d}$ and EDT as a function of r. For the stages, every graph shows results per source position. For each orchestra pit a grouping
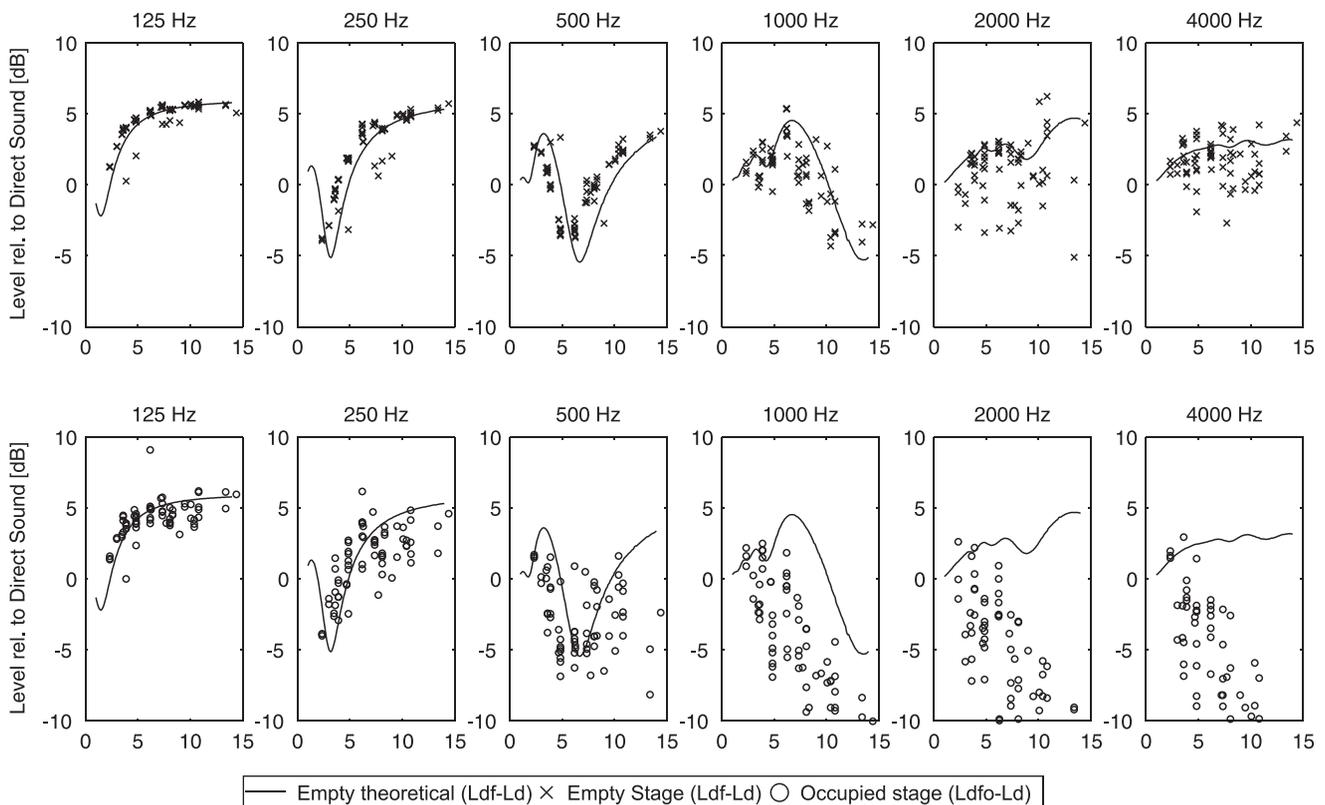
FIG. 9. Individual data points for L_{df}-L_d in upper graphs and L_{dfo}-L_d in lower graphs as a function of r. The lines represent theoretical values for L_{df}-L_d in all graphs.
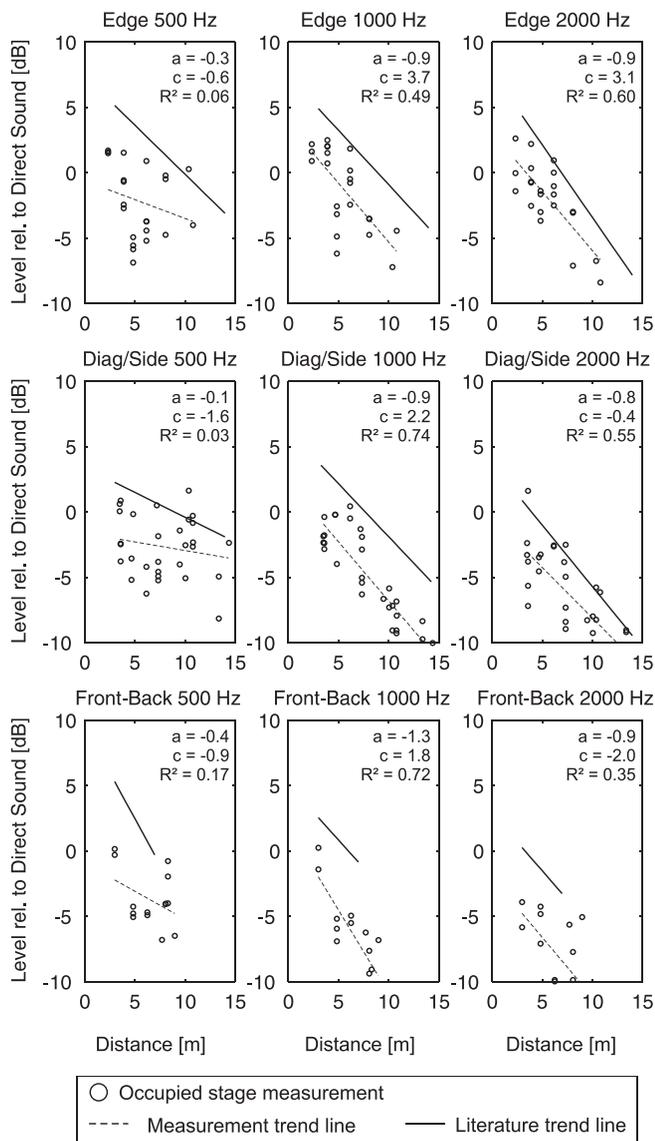
FIG. 10. Individual data points for L_{dfo}-L_d as a function of source–receiver distance for the octave bands 500, 1000, and 2000 Hz. Edge = sound path along the edge of the orchestra, Diag/Side = sound path diagonal or sideways, Front–Back = sound path from front to back in the middle of the orchestra. Dashed lines are linear trend lines for L_{dfo}-L_d based on the measured data. The coefficients a and c for the trend line with equation a x r +c are given for each line together with the correlation coefficient R^2. The solid lines are trend lines as suggested by Dammerud and Barron (Ref. 7).

is used which has shown to be typical for orchestra pits:[19] both positions in the open part (O–O); just one of both positions in the open or covered part (O–C); and both positions in the covered part (C–C).

Besides EDT per distance, the position average T_{20} is presented as lines because it showed few variation over distance. To investigate the overall effect of the chairs, stands and mannequins on $ST_{early,d}$, Fig. 12 shows the differences in $ST_{early,d}$ for all measurements on all stages and pits as a function of r.

For the measurements at 1 m distance, averaged over the five stages, the $ST_{early,d}$ was higher than the original ST_{early} by 2 dB in the empty state and by 3 dB in the occupied state (similar to earlier findings as mentioned in Sec. II D). For

ST_{early} at 1 m distance the absolute difference between the empty and occupied state is 1.6+/−1.4 dB and for $ST_{early,d}$ at 1 m distance 0.9+/−0.7 dB.

D. Late sound results

The distance averaged $ST_{late,d}$ did hardly differ from ST_{late} measured at 1 m distance by more than 1 dB and $ST_{late,d}$ is chosen for further analyses. Figure 13 shows the average $ST_{late,d}$ per stage for all positions and per orchestra pit for the three groups O–O, O–C, and C–C. One might expect that the late arriving energy can be described as being part of the diffuse sound field. Following Barron's revised theory,[20] ST_{late} or $ST_{late,d}$ can be predicted by the room volume V and reverberation time T:

$$ST_{late} = 10 \lg \left[\frac{31200T}{V} e^{-(13.82 \times 0.103/T)} \right] - 20. \qquad (3)$$

Alternatively, it can be written as

$$ST_{late} = 10 \lg(312T/V) - 6.2/T. \qquad (4)$$

For the empty stages with a well-defined room volume [concert hall (CH) and rehearsal room (RH)], $ST_{late,d}$ is predicted using Eq. (3) with 0.1 and 0.3 dB deviation from the measurements for the CH and the RH, respectively, which suggests that the revised theory holds for the empty stage. For the CH and RH, we investigated whether the difference in $ST_{late,d}$ could be explained by a measured 5% reduction in T. Based on the reduction in T, the addition of the chairs, stands and mannequins would only lead to −0.3 and −0.5 dB difference, while the measured difference is −1.7 and −4.1 dB.

IV. DISCUSSION

A. Direct sound

The interference of the direct sound with the floor reflection on the empty stage floor corresponds well with theory for the lower frequencies up until the 500 Hz octave band, see Fig. 9, although the theoretical curve is shifted by approximately 1 m. Small changes of 0.1 m in geometrical properties used in the analytical model can cause such a shift. At 1000 Hz and above, measured values deviate from theory resulting in both higher and lower values for L_{df}-L_d. Most of the variation can be explained by the directivity of the sound source at these frequencies (uncertainty of +/−2.8 dB, see Sec. II C).

The direct sound level is reduced at most positions when the stage is fully occupied. This consistency shows that the reduction in sound level by absorption and scattering is larger than the increase of sound level by 'within orchestra reflections'. In the frequency bands 500, 1000, and 2000 Hz, L_{dfo}-L_d is consistently lower in our study compared to D&B with a constant shift over all distances varying from −3 to −6 dB. This shift brings the reduction of sound close to the source nearer to 0 dB compared to the trend lines by D&B. The uncertainty introduced by the directivity of the sound source can explain the variation, but cannot explain our values being consistently lower. Consistent deviations could be
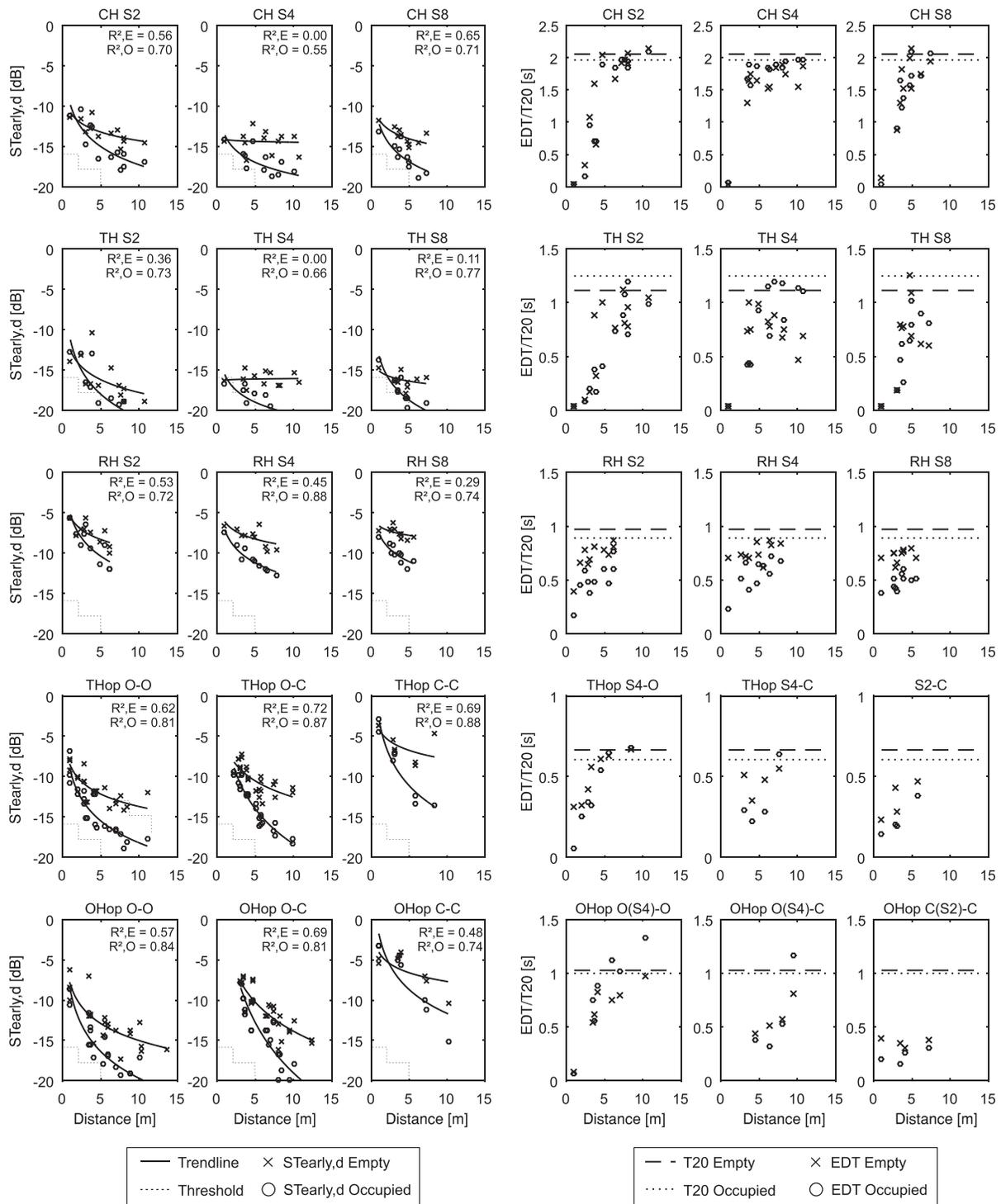
FIG. 11. Individual data points for $ST_{early,d}$ (left) and EDT (right) as a function of source–receiver distance r for the empty and occupied stages and pits (250 to 2000 Hz average). The dashed line in the $ST_{early,d}$ figures, including the x axis above 5 m, represents the threshold. The dashed lines in the EDT figures represent the distance averaged reverberation time T_{20}, for both unoccupied and occupied stage. S2, S4, S8 = source position 2, 4, and 8, O–O = open–open, O–C = open–covered, C–C = covered–covered. R^2,E and R^2,O = correlation coefficient, empty and occupied.

caused by uncertainty in the sound power of the source. However, D&B[7] explain in their paper that, after calibration, measured G_{df} corresponded well with theory and our calibration procedure has a uncertainty of only 0.8 dB.[21] Also, the measured sound absorption of our mannequins and their scale model orchestra are in the same order of magnitude at frequencies 1000 and 2000 Hz, see Fig. 5. Considering all these factors, we must conclude that the attenuation of sound passing through our full scale orchestra is indeed 3–6 dB more at each distance than through the scaled orchestra by D&B.

B. Early sound

The early reflected sound level, measured by $ST_{early,d}$, tends to decrease as a function of r for most source positions

J. Acoust. Soc. Am. **140** (6), December 2016

Wenmaekers *et al.*   4445
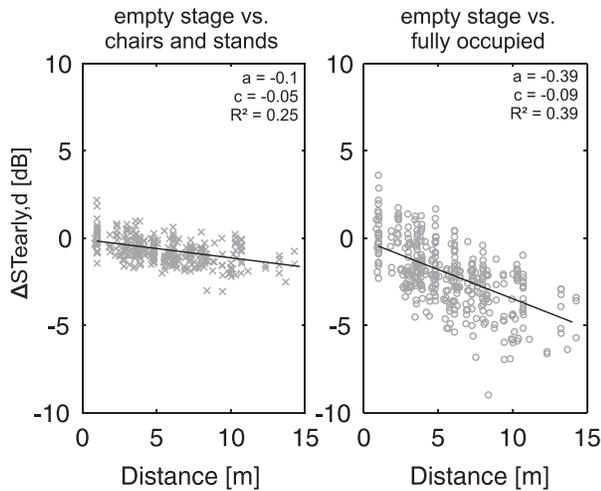
FIG. 12. Difference in $ST_{early,d}$ as a function of source–receiver distance for all measurements of all stages. Left: empty floor minus floor with chairs and stands. Right: empty floor minus floor occupied with mannequins.

or source–receiver groups in both unoccupied and occupied conditions, see Fig. 11. In case the source is near a stage wall, the path length of the reflection from that wall increases with the distance to the receiver r and as a result, the sound energy decreases with r for that particular reflection. Because this wall reflection is dominant in the parameter, the total early reflected sound energy will decrease with r. The attenuation by the orchestra also increases when reflection path lengths through the orchestra increase. For source positions close to walls, and for relatively small stages and pits, this explains the general tendency that the early reflected sound is reduced by the orchestra increasingly as a function of r.

When the sound source is located in the middle of the orchestra, $ST_{early,d}$ on the unoccupied concert hall and theatre stages at S4 show no correlation with r. Surprisingly, $ST_{early,d}$ does correlate reasonably well with the r for S4 and S8 when the orchestra is included (for CH, R^2 is 0.55 and 0.71, and for TH, R^2 is 0.66 and 0.77). At these positions and
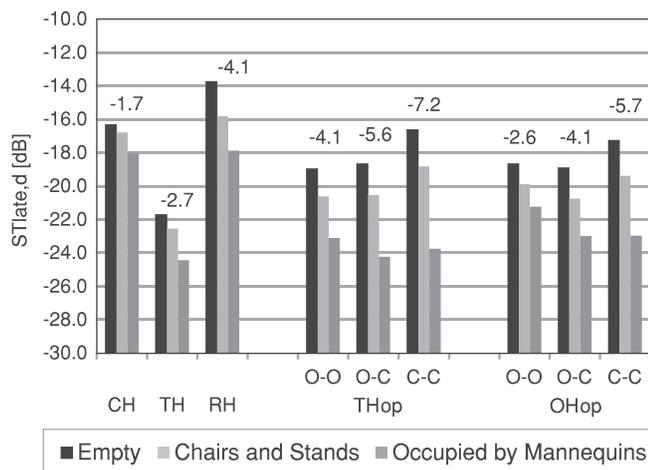
FIG. 13. Average $ST_{late,d}$ per stage and pit for the empty condition, the condition with chairs and stands, and the condition with chairs, stands and mannequins. Numbers in the graph represent the difference between empty floor and fully occupied conditions.

stages, $ST_{early,d}$ is close to the measurement threshold. In that case, measured $ST_{early,d}$ increases by the presence of the orchestra at short distance due to 'within orchestra reflections' and decreases at further distance. This is likely the reason why the overall measured $ST_{early,d}$ also decreases as a function of r on these stages at source positions in the middle of the orchestra.

The EDT shows an increase as a function of distance for both unoccupied and occupied conditions, but the trend is not as clear as for $ST_{early,d}$. On some stages/pits, EDT approaches T_{20} at larger distances and EDT is 0 s at 1 m distance because of the strong direct sound component. On the large stages CH and TH, the difference in EDT between empty and occupied state can both be positive and negative. In the smaller "rooms" (RH stage, THop, and the covered part of OHop), EDT is systematically reduced by the presence of the orchestra similar to its reduced T_{20}. Possibly, this reduction might be this consistent because both the early and late sound field contains of a larger number of reflections in a small space and direct sound is less dominant. In contrary, EDT increases when the orchestra is present in the open area of the large orchestra pit (OHop), which might indicate that the direct sound is more reduced than the early reflected sound is. It could be expected that the EDT frequency balance, EDTF, would increase when the mannequin orchestra is on stage because of the largest attenuation in the high frequencies. However, no significant stage-average differences for EDTF were found and the average standard deviation of differences in EDTF per stage was high ($\sigma = 0.4$).

The difference between $ST_{early,d}$ in occupied and unoccupied state is presented in Fig. 12 for all single measurements. The average distance dependant reduction of $ST_{early,d}$ due to the orchestra as a function of r, is not significantly different per stage or pit. A linear trend can be observed with a low correlation and the largest variance in the condition with the orchestra present. No significant difference was found for source–receiver combinations along the edge of the stage and combinations in the middle of the stage. The variation might therefore be attributed to the irregular pattern of the objects combined with the complexity of multiple reflection paths. The reduction in dB/m by chairs, stands and mannequins is four times larger than the reduction by chairs and stands only. This shows that unoccupied chairs with stands cannot simulate a stage being occupied by a full orchestra; one might as well measure on an empty stage which is more convenient.

Because the variation of $ST_{early,d}$ and EDT over distance is different per stage, judging the amount of early reflected sound on stage based on solely 1 m distance measurements can limit the judgment of the stage's performance. However, as Dammerud[10] concluded, an advantage of measuring close to the source is that ST parameters are least influenced by the presence of the orchestra. When comparing the original ST_{early} to $ST_{early,d}$ measured at 1 m, it seems that $ST_{early,d}$ is least influenced. When considering a JND of 2 dB for the ST parameters, as estimated by Gade, the influence of the orchestra could be neglected when measuring $ST_{early,d}$ at 1 m distance but could be relevant for measurements at larger distances. For original ST_{early}, the influence of the orchestra

is just above 2 dB. For EDT, most of the measured results were influenced by the orchestra above the JND of 5% and an occupied stage might be necessary for valid measurement. Changes in EDT due to occupation are not consistent and more research is necessary to determine the reliability of this parameter for the use on stage.

C. Late sound

Most stages show a reduction in the average reverberation time T_{20} of 5%–10% after putting the orchestra on stage as can be expected.[17,22] One exception is the TH at which the T_{20} increased. Possibly, placing the mannequins in the more reverberant side stage (behind the stage curtains) for storage had a larger effect on the average T_{20} of these coupled spaces.

The late reflected sound, measured by $ST_{\text{late},d}$, is reduced by the presence of the orchestra much more than Barron's revised theory predicts, see Fig. 13. It seems that part of the sound energy is absorbed and screened in propagation paths through the orchestra. The amount of reduction seems to depend on the "virtual stage volume" and its connection to the hall. The smaller and less exposed the stage to the hall is, the more the late reflected sound is reduced by the orchestra. The following can be observed:

- When comparing the concert hall and theatre: while both stages were occupied by the same orchestra setup, having equal absorption properties, $ST_{\text{late},d}$ is influenced more by the orchestra in the non-reflective theatre stage compared to the reflective concert hall stage;
- when comparing the two orchestra pits: the open/uncovered area is smaller in THop compared to OHop, resulting in a larger reduction in $ST_{\text{late},d}$ when occupied by the orchestra. Also, the orchestra has a larger impact on $ST_{\text{late},d}$ for positions under the stage overhang compared to positions in the open area.

V. PRACTICAL EXAMPLE

For most survey measurements, using a mannequin orchestra would be too time-consuming and expensive. Therefore, we investigated how a measurement can be performed with a real (professional) orchestra in the CH in a short time span with a signal that is comfortable for musicians. Three sources and six receivers were used at the locations as suggested by Gade,[1,5] see Fig. 14. To avoid cables, six recorders (TASCAM DR-40) were used with six omnidirectional microphones (DPA 4060). The sound source (B&K type 4292) and amplifier (AE Amphion) with an external battery pack were portable. Another recorder played back a 5.46 s Maximum Length Sequence (MLS) signal repeated twice proceeded by a voice countdown. The loudness of the MLS signal was set just below 90 dB(A) at the nearest seating distance.

The measurement took place at the start of a rehearsal and all transducers were in place before the entrance of the orchestra members. The musicians were informed in advance via an online website and video. After playing the signal once on stage, all musicians accepted to participate
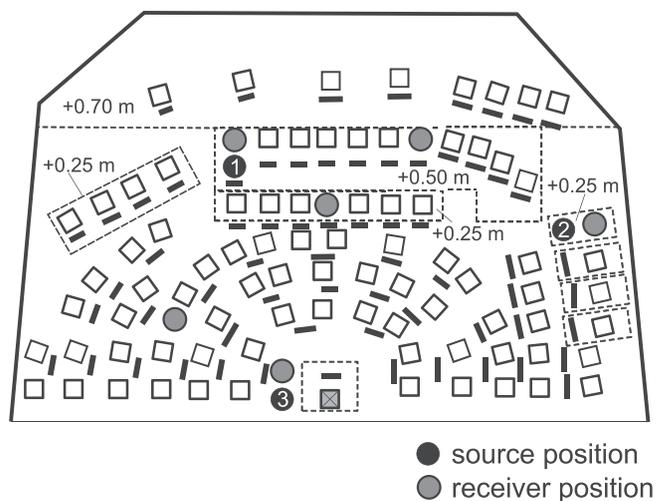
FIG. 14. Source and receiver positions used for the measurements with the real orchestra, as suggested by Gade (Refs. 1 and 5).

● source position
● receiver position

without hearing protection. With the help of four persons, it took 6 min to play the signal at all three source positions. The musicians were asked to hold their instruments in still playing position while being silent for 20 s during each measurement. The actual rehearsal started four minutes after removing all equipment while marking the transducer positions with tape. During a short rehearsal break the distances between tapes were measured to obtain the exact r.

In the laboratory, a sound power calibration was performed in a reverberation room. Impulse responses were obtained using software Dirac 6.0 (B&K type 7841) which corrects for device clock speed errors (necessary for an asynchronous measurement). The impulse response decay ranges (INRs) at 1 m exceeded 38 dB with an average of 46 dB and at larger distances the INR exceeded 29 dB with an average of 34 dB. Based on these INRs, it is expected that $ST_{\text{early},d}$ and $ST_{\text{late},d}$ are calculated within 0.2 dB error, which is lower than the uncertainty for not rotating the source.

The measurement results of $ST_{\text{early},d}$ are presented in Fig. 15 together with earlier measurements with the mannequin orchestra. The trend lines of both occupied measurements only differ by 0.5 dB on average and a similar variation along the trend line can be observed. The average result for $ST_{\text{late},d}$ of both measurements differed only by 0.2 dB. Based on these results, we can conclude that "musician friendly" stage acoustic measurements can be done within 10 min time.

VI. CONCLUSION AND RECOMMENDATION

The direct, early and late sound on stage, measured by $ST_{\text{early},d}$, $ST_{\text{late},d}$, EDT and T_{20} at various distances, is significantly influenced by the orchestra. Original ST_{early} (with a 20–100 ms time window) varies just above the estimated JND of 2 dB while $ST_{\text{early},d}$ at 1 m distance (with a 10–100 ms time window) varies just below the JND. The late reflected sound level in most stages and pits, measured by ST_{late} or $ST_{\text{late},d}$, is reduced above the estimated JND and considerably more than can be expected based on Barron's revised theory.

J. Acoust. Soc. Am. **140** (6), December 2016

Wenmaekers *et al.* 4447

Orchestra versus Mannequins
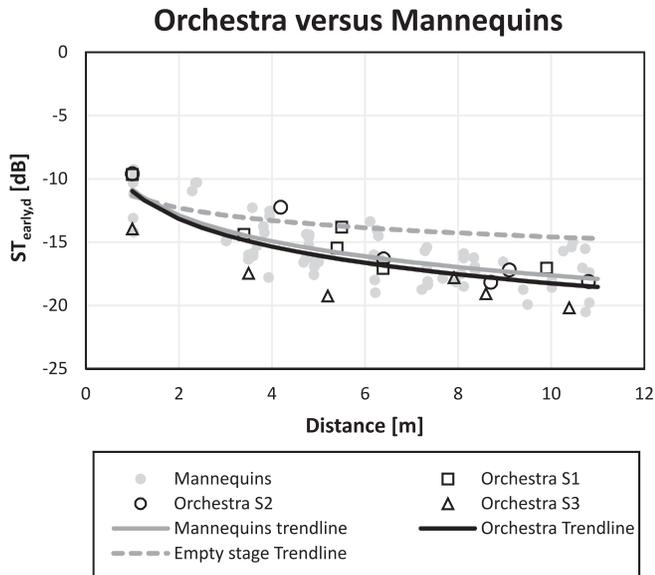
FIG. 15. Individual data points for $ST_{\text{early},d}$ as a function of source–receiver distance for the same concert hall stage occupied by the real orchestra and the mannequin orchestra. The lines represent the logarithmic trend line of all measurements with the real orchestra and the mannequin orchestra.

It is clear that significantly different values of stage acoustic parameters are found on occupied stages compared to unoccupied stages, even at 1 m distance. Chairs and stands on stage, as suggested in ISO 3382-1, do not substitute a real orchestra; one might as well measure on an empty stage. For extensive research a mannequin orchestra has shown to be an accurate but time-consuming method. Survey measurements can be done with a real orchestra within 10 min with results showing reasonable agreement with those by the mannequins.

Further research should focus on:

- Correlation between perceptual attributes and parameter values when being measured on occupied stages and/or distances above 1 m.
- The importance of directivity of the musical instruments and musicians' ears.
- Methods to correct parameters measured on empty stages or model values for occupied stages.

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