

# Why orchestral musicians are bound to wear earplugs: About the ineffectiveness of physical measures to reduce sound exposure

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## Chapter 7

# Orchestral musicians' sound exposure

Original title: Why orchestral musicians are bound to wear earplugs: about the ineffectiveness of physical measures to reduce sound exposure

Authors: R.H.C. Wenmaekers, B. Nicolai, M.C.J. Hornikx, A.G. Kohlrausch  
Submitted

### **Abstract**

Symphony orchestra musicians are exposed to noise levels that put them at risk of developing hearing damage. This study evaluates the potential effectivity of common control measures used in orchestras on open stages with a typical symphonic setup. A validated acoustic prediction model is used that calculates binaural sound exposure levels at the ears of all musicians in the orchestra. The model calculates the equivalent sound levels for a performance of the first 2 minutes of the 4th movement of Mahler's 1st symphony, which can be considered representative for loud orchestral music. Calculated results indicate that risers, available space and screens at typical positions do not significantly influence sound exposure. A hypothetical scenario with surround screens shows that, even when shielding all direct sound from others, sound exposure is reduced moderately with the largest effect on players in loud sections. In contrast, a dramatic change in room acoustic conditions only leads to considerable reductions for soft players. It can be concluded that significant reductions are only reached with extreme measures that are unrealistic. It seems impossible for the studied physical measures to be effective enough to replace hearing protection devices such as ear plugs.

## 7.1 Introduction

Most classical musicians are regularly exposed to a daily noise exposure level above 80 dB(A) and therefore risk hearing damage [1]. The relation between noise exposure and hearing damage has been investigated for orchestral musicians in the past 25 years [2]. Musicians appear to perform better in hearing tests than a comparable general population, possibly due to a selection bias [3]. Nevertheless, musicians do have a work-related risk of developing hearing disorders such as hearing loss [3], tinnitus and presbycusis [4, 5]. Researchers have not always found alarming hearing damage among classical musicians [6]. Still, most researchers do advise that sound exposure levels should be reduced [3, 5, 7, 8] if only because any unnecessary hearing damage is undesirable [9]. The current chapter is mostly concerned with the reduction of equivalent sound levels and the following literature review will focus on research dealing with causes and possible solutions.

A number of researchers have measured the sound exposure of musicians which could reveal the effect of the physical environment on sound levels. However, it is difficult to compare results across studies because time averaging methods vary [10]. Researchers used dosimeters attached to the shoulder or microphones on stands, while [11] promotes the use of miniature microphones attached near both ears of the musicians. Also, factors such as changing seating position and different repertoire make the interpretation of results difficult. For instance, O'Brien et al. [12] found that the long-term exposure in a symphony orchestra varied between three different venues by 0 to 4 dB, depending on the studied musician. The mean exposure was slightly lower in the rehearsal room compared to the concert hall and higher in the orchestra pit. In the orchestra pit, a generally more intense repertoire was played that could explain the higher sound levels. The lower levels in the rehearsal room are explained by breaks with speech that reduce the equivalent sound levels. According to Gade [13], musicians might play more passionately and thus louder during performances which could also explain lower sound levels during rehearsals. Finally, the three venues likely also vary in room acoustic conditions possibly increasing sound levels in the rehearsal room and orchestra pit. O'Brien et al. [14] also investigated  $L_{A,eq}$  during individual rehearsal (averaged over 20 min.), which were higher than  $L_{A,eq}$  in the orchestra (averaged over many performances) by +3 to +5 dB for high strings and up to +7 dB for flute and brass. The higher sound levels during individual rehearsal are likely caused by more intense playing with fewer breaks compared to orchestral rehearsal or performance. Exceptions are the cello and contrabass who receive -4 and -9 dB lower levels, respectively, because these instruments are less powerful in the mid to high frequencies compared to other instruments in the orchestra. These results suggest that most musicians would be better off in terms of sound exposure per unit of time playing in the orchestra instead of practicing individually, which is highly counterintuitive. To investigate the contribution of the own instrument to the sound levels in the orchestra, Schmidt et al. [11] compared active and inactive periods. It was shown that most instrument groups, except low strings, have a significantly higher exposure when playing. It was concluded that, even in the orchestra, musicians are primarily exposed to their

own instrument. If the own instrument is contributing most to the total sound exposure, then rotating positions in the same section would not be an effective measure to control sound exposure. Indeed, Schmidt et al. [11] did not find any statistical difference in exposure among musicians within the same group.

Other studies have been dedicated to the effect of screens that are used to shield musicians from loud instruments. Gade et al. [15] sent questionnaires to 46 opera houses. 23% of the orchestras used screens in the orchestra pit and screens were only used if there was sufficient space (2 m<sup>2</sup> per musician). Camp and Horstman [16] measured the effect of a free standing plastic screen (unknown dimensions) between two neighbouring positions in an orchestra pit using a loudspeaker and a single microphone and found reductions of -1, +2, -8, -9, -13 and -15 dB for the mid pure tone frequencies of the octave bands 125 to 4,000 Hz. The authors of the current work repeated this experiment with a floating 12 mm wooden panel with dimensions 1 x 1 m<sup>2</sup>. A head and torso simulator was positioned with its ears at 30 cm distance from the middle of the screen and a directional sound source on the other side at the same distance. Impulse responses were measured with and without the screen and the difference in sound pressure level was determined in octave bands. Good agreement was found with the measured data from Camp and Horstman for most octave bands except for the 500 Hz band that showed considerable smaller values: -3 dB instead of -8 dB. According to [17], a screen with absorptive material that is wrapped around the back of the head shows similar reductions while additionally avoids sound being reflected back to the source. The screens on stands are often found ineffective because musicians have to sit uncomfortably close to them [18, 19]. As an alternative, O'Brien et al. [19] experimented with a tall shielding barrier. The measured attenuation by the screen was 3 to 4 dB(A) with two trumpet players at 1.5 m distance to the screen and the microphone on the other side at 0.5 m from the screen. Results from these studies should be interpreted with care because they do not include the sound of other players that can reduce the effect of screens. In the study by Libera and Mace [18], both higher and lower sound levels were observed after introducing screens while the whole orchestra was playing in a small rehearsal room. Martinez [20] measured reductions of only 1 dB(A) on both sides of a large 10 m wide and 2.3 m high barrier between the strings and the other sections, also in a rehearsal room. In contrast, O'Brien et al. [19] measured a reduction of 4 to 6 dB(A) while the whole orchestra was playing in a pit when introducing the barrier screen between a cello player and the trumpets.

Chasin [21] mentions the possible effect of risers on the reduction of sound exposure. He measured a reduction in sound pressure level of 5 to 7 dB in the high frequencies at positions in front of the trumpets when placing trumpet players on risers. This reduction is achieved because of the strong directionality of the trumpet at high frequencies. However, Eaton and Gillis [22] point out that the mid-frequency components (say, 500-2000 Hz) of the trumpet are most powerful compared to the higher frequency bands. As a result of a lower directivity at mid frequencies, the actual reduction of overall sound exposure by placing trumpets on risers might be much lower than suggested by Chasin.

Researchers have suggested room acoustic guidelines to control sound levels, focussing on orchestra pits and rehearsal rooms instead of concert hall stages. Tennhardt & Winkler [23] give detailed suggestions for rehearsal room design. They noted that, in contradiction to what was believed earlier, the goal should not be to reproduce the same acoustic conditions as in the performance venue. They suggest a reverberation time ( $T$ ) as low as 0.8 to 1.1 s which would allow smaller rooms without increased sound levels compared to concert halls. Gade et al. [15] found that most orchestra pits had no high frequency absorption materials inside and 70% had a wooden finish. They suggest that absorption in the pit should indeed be avoided because it would lead to reduced support and musicians would play louder if they cannot hear themselves or colleagues. For rehearsal rooms, Gade [13] suggested that there might be less need to play powerful due to more support in smaller rooms. However, this can only lead to an improvement if the increase in sound levels due to the smaller room is less than the reduction in sound power produced. Therefore, Gade [13] suggests to introduce at least 8 m<sup>2</sup> of equivalent sound absorption area,  $A$ , per musician in symphony orchestra rehearsal rooms, leading to a room volume ( $V$ ) between 5.000 and 10.000 m<sup>3</sup> for a 100-person symphony orchestra. Some researchers have used the stage acoustic parameters  $ST_{early}$  or  $ST_{late}$  to derive recommendations for the room volume of rehearsal rooms.  $ST_{early}$  describes the dB ratio of early reflected sound energy between 20 and 100 ms and the direct sound energy, both measured at 1 m distance for the sound source. Similarly,  $ST_{late}$  describes the dB ratio of late reflected sound energy after 100 ms and the direct sound energy. Pompoli et al. [24] suggested the amount of early reflected sound, measured by the stage acoustic parameter  $ST_{early}$ , as a guideline to control sound levels in rehearsal rooms. Considering a suitable value for  $ST_{early}$  of -12 dB (+/-2 dB), rehearsal rooms require a  $V$  between 750 and 2,500 m<sup>3</sup>. Additionally, Wenmaekers et al. [25, see section 9.3] used the late reflected sound level ( $ST_{late}$ ) to obtain requirements for  $V$  and  $T$ , resulting in  $V \geq 2,000$  m<sup>3</sup> for  $T \geq 1.0$  s. Another guideline is presented in the Norwegian standard NS-8178 “Acoustic criteria for rehearsal and performance spaces”, see Rindel [26]. A recommended range of  $V$  and  $T$  is given for powerful acoustical music with a maximum  $V$  of 3,000 m<sup>3</sup>. In an informative section of the standard, a prediction model is presented that calculates the sound levels in the room for a given ensemble to obtain guidelines for room volume. In contrast, Lautenbach and Vercammen [27] suggest that large rooms ( $V > 8,000$  m<sup>3</sup>) are highly preferred over relatively small rooms ( $V = 4,000$  m<sup>3</sup>). Figure 7.1 summarizes all mentioned requirements. It is clear that the mentioned strategies lead to different requirements for  $V$  and  $T$ . With a reverberation time of 1.1 s, four guidelines overlap at a volume of approximately 2,000 m<sup>3</sup>. Gade’s guideline results in a much large volume (4,500 m<sup>3</sup>) when the reverberation time would be 1.1 s. Only for reverberation times around 1.7 s, Gade’s guideline and the guideline based on a  $ST_{late}$  of -13 dB are similar.

If measures at the source are not sufficient to reduce the daily noise exposure level below 85(A), individual hearing protection must be worn [1]. Moulded ear plugs can easily reduce sound levels by 20 dB or more. However, several studies have shown that musicians are

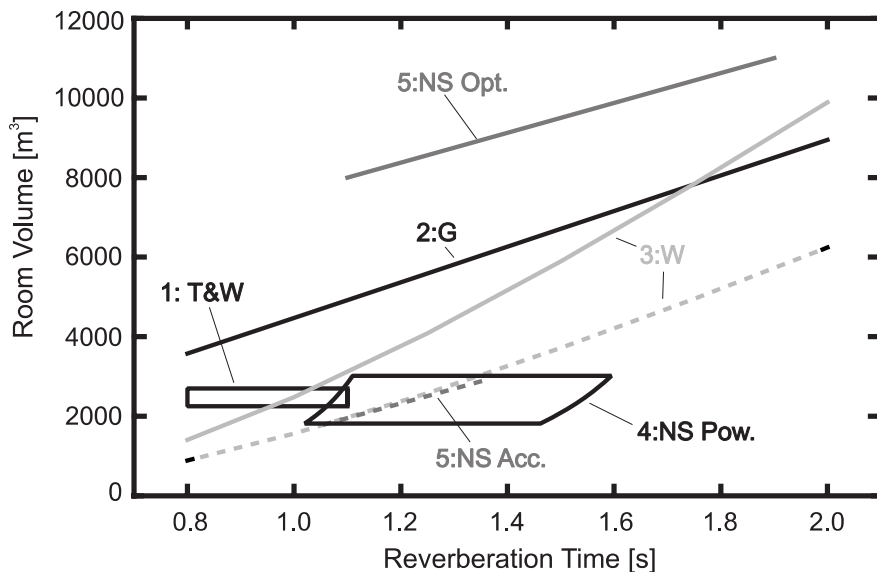


Figure 7.1. Summary of guidelines suggested in literature for rehearsal rooms with an orchestra comprising 90 musicians:

- 1: Tennhardt and Winkler [23], 25-30 m<sup>3</sup> per musician and T = 0.8-1.1 s and V<sub>min</sub> = 2,000 m<sup>3</sup>;
- 2: Gade [13], A = 8 m<sup>2</sup> per musician;
- 3: Wenmaekers et al. [25], ST<sub>late</sub> = -13 to -15 dB, predicted by  $10 \log (312T/V) - 6/T$ ;
- 4: NS-8178 [26], T and V range for powerful music, V<sub>min</sub> = 1,800 m<sup>3</sup> and V<sub>max</sub> = 3,000 m<sup>3</sup>;
- 5: NS-8178 [26], prediction model  $L_{p,A,diff} = L_{w,A} + G - 31$  dB, symphony orchestra  $L_{w,A} = 115$  dB, G is 6 dB for optimal conditions ( $L_{p,A,diff} = 90$  dB at forte) and G is 11 dB for acceptable conditions ( $L_{p,A,diff} = 95$  dB at forte).

reluctant to wear ear plugs or other hearing protection devices (HPDs) [28, 29, 30], and mostly wear them when hearing problems already exist [3]. The main reasons are that HPDs hinder the own performance and make it difficult to hear others play [26]. Nevertheless, there are reports of successful ear plug use by musicians [31]. If HPDs are used, they are worn during group or orchestral rehearsal and very rarely during individual rehearsal because ‘musicians feel their own instrument is not noisy, but it is the neighbouring instruments that cause the problems’ [28]. They might even think that they themselves are worse off than their neighbours causing the noise: ‘It is a logical assumption that the players directly in front of the trumpets are exposed to a much higher level than the trumpet players themselves; however, this was routinely not the case.’ [12].

It is clear that there is a desire to control sound levels in orchestras preferably by using physical measures. However, sound exposure measurements have not been conclusive on their effectiveness. Small scale experiments with screens or barriers are either too optimistic or too specific to lead to general conclusions. Various acoustic guidelines lead to different solutions and their effect on sound exposure has not been validated. In the current chapter,

the prediction model as presented in the previous chapter is used to investigate the effectiveness of the following common physical measures that aim at controlling sound levels in orchestras:

- Increasing the distance between musicians
- Changing the height of risers
- Using absorptive screens
- Changing the acoustic properties of the room
- Rotating the position of musicians

In the next section 7.2 the modelling method will be briefly summarised accompanied by a comparison to measurements. In section 7.3, the model is used to study the possible control measures. The chapter ends with a conclusion.

## 7.2 Method

### 7.2.1 Sound level distribution model

A sound level distribution model for symphony orchestras is used as presented by Wenmaekers and Hak [32, see [chapter 6](#)], updated and programmed in Matlab by Nicolai [33]. A schematic overview of the model is given in Figure 7.2. The model will be briefly summarised here. See [chapter 6](#) [32] for details and equations and the thesis [33] for more background information.

The model calculates direct sound, early and late reflected sound separately, using anechoic recordings to obtain the sound power of each instrument. The binaural direct sound level is calculated analytically. At the source, the directivity characteristics of each instrument and the geometry of the orchestra members' seating positions are used to determine the directional sound power. The interference of the floor reflection for low frequencies and the attenuation by the orchestra members at high frequencies are taken into account based on measured data [30]. At the receiver position, directional weighting is applied for the two ears using a Head Related Transfer Function (HRTF) measured with microphones in front of the ears of a dummy head. A special contribution is the modelling of the direct sound of the own instrument. The distances and angles between the estimated acoustic source centre of each instrument and each ear have been measured to be used in the model.

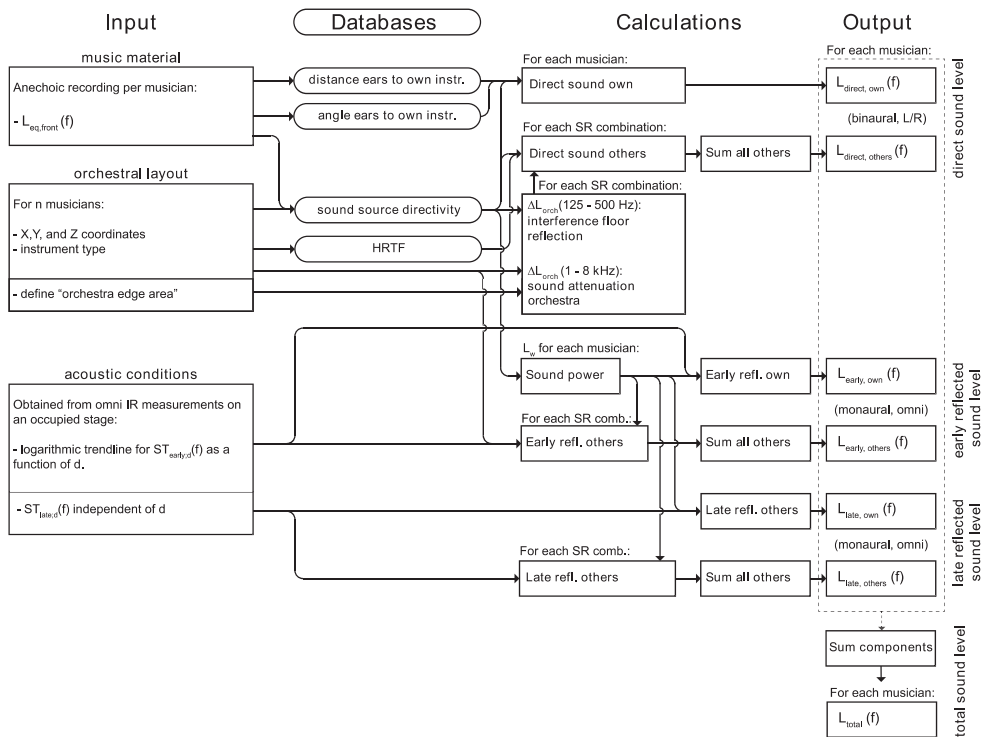


Figure 7.2. Overview of the sound level prediction model by Wenmaekers and Hak [32, see [chapter 6](#)], updated and programmed in Matlab by Nicolai [33]. Figure 3.2 in [33].

Secondly, the monaural sound level from reflected sound wave contributions is calculated based on impulse response measurements on occupied stages at various distances using omnidirectional transducers [34, see [chapter 4](#)]. Stage acoustic parameters  $ST_{early,d}$  (distance dependent) and  $ST_{late,d}$  (fixed values) are calculated which use a time point of 103 ms relative to the time of emission to separate early from late reflections [35, 36 see [chapter 2](#)]. The  $ST$  parameters compare the reflected sound energy to the sound power measured in a reverberation room [37, see [chapter 3](#)]. The directivity of the instrument is not taken into account for the calculation of the sound level of reflected sound, which has shown to have a negligible influence ( $< 2$  dB) in the frequency bands with the largest contribution to the A-weighted sound level (500-1000 Hz) [38, see [chapter 5](#)]. In the model, the sound power of the instruments is combined with the measured  $ST$  parameters to obtain the absolute early and late reflected sound levels for every combination of two musicians. The monaural sound energies are summed with the binaural direct sound energy at each separate ear to obtain the total sound level per ear. Equivalent sound levels can be obtained for the whole Mahler piece or shorter time intervals can be studied such as the running average of  $L_A$ .



To estimate the effect of screens, the musician to musician direct sound is attenuated by the reduction of a single screen (-1, +2, -3, -9, -13 and -15 dB for the octave bands 125 to 4,000 Hz, see section I). The model does not take into account distance dependent screening, which is reasonable because the receiver is very close to the screen (0.3 m) compared to the source at larger distance. This simplification results in an overestimation of the screening effect at larger mutual distance, but because these levels are less dominant in the total level it is expected to have a small influence on total levels. It is assumed that the screen has no influence on reflected sound levels, which is a reasonable assumption in the case of sound absorbing screens.

## 7.2.2 Measurements

Available anechoic recordings of each separate instrument from the first 2 minutes of the 4th movement of Mahler's 1st symphony titled 'Stürmisch bewegt' are used as an input for the model [39]. The piece is a typical example of a loud passage with all instruments simultaneously and alternatingly playing. Measurements have been performed with a symphony orchestra that played the same music to validate the model. Besides, scales were measured played by individual players and whole instrument groups. Ten musicians that volunteered to play individually, see Figure 7.3, were equipped with binaural DPA 4060 microphones positioned 1–2 cm lateral to the entrance of the ear canal of both the left and right ear using custom-made ear holders. Both the music and a calibration tone were recorded with a TASCAM DR-40. The digital signal processing was performed in MATLAB 2014b. The expected accuracy of the sound level measurements is +/-2 dB, which approximates the tolerance of a Type 2 sound level meter in the 500 and 1,000 Hz octave bands where sound levels in the orchestra have shown to be dominant [40].

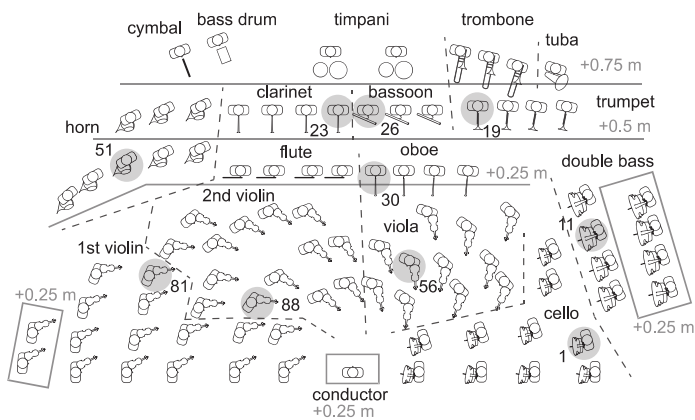


Figure 7.3. Floor plan of the orchestra in MGE with the positioning of the 10 musicians that were measured (grey circles). The numbers are used to define the sound source in the model. Figure 4.3 in [33].

Measurements were undertaken in three different venues during a rehearsal on stage: a concert hall denoted ‘MGE’ ( $T_{500-1k}=1.8$  s,  $V=14,400$  m<sup>3</sup>), a theatre with an orchestra shell denoted ‘VTM’ ( $T_{500-1k}=1.3$  s,  $V=12,000$  m<sup>3</sup>) and a theatre with an orchestra shell and electroacoustic enhancement denoted ‘PDB’ ( $T_{500-1k}=1.6$  s,  $V=13,000$  m<sup>3</sup>). The 95-person orchestra occupied approximately 200 m<sup>2</sup> in each hall. Surprisingly, after performing all measurements it turned out that the rooms had almost equal values related to early and late reflected sound, namely  $ST_{early,d} = -15.5 \pm 0.7$  dB and  $ST_{late,d} = -17.9 \pm 0.3$ , respectively.

### 7.2.3 Comparison for the scales

Figure 7.4 shows the calculated and measured  $L_{A,eq}$  as a result of the 1st violin player (no. 81) playing a scale. The  $L_{A,eq}$  distribution is shown over the positions in the orchestra for both ears together with the interaural level difference (ILD). The sound power of the individual player is predicted using the measurement at his right ear. As can be seen in the scatter plots, the model and measurements show a similar large difference between  $L_{A,eq}$  at the player’s ear and those of the other musicians with a slight decay over distance for the other musicians.

The scale was played individually by the ten musicians in 3 different halls. The mean absolute deviation (MAD) between calculated and modelled  $L_{A,eq}$ , averaged over the 9 inactive players, varies between 1 and 4 dB for the different instruments and halls. The best agreement between measurement and model is observed for the viola, French horn and clarinet with  $MAD < 2$  dB and standard deviation (SD)  $< 1.5$  dB over the 9 receiver positions for all 10 source positions in 3 venues. The 1st violin, 2nd violin, bassoon and trumpet show a slightly larger  $MAD < 2.5$  dB with  $SD < 2$  dB. The cello, double bass and oboe show a poorer agreement with the model, with a maximum MAD of 3.8 dB for double bass in PDB.

In the model, it is assumed that all players with the same part play equally loud. For the scale experiment, each musician in a group is modelled using the sound power of the individual player. The modelled group results are compared to the measurements with groups. The overall results are similar to the situation with scales played individually, with  $MAD < 4$  dB in most cases. Two exceptions are the 1st violin and the double bass groups with a MAD up to 8 dB, which suggests that the individual player’s colleagues in these groups played much louder than the individual player did. These exceptions demonstrate a limitation of the experiment; it seems difficult for other players to reproduce the individual player’s strength for a single scale. Extensive results of the scale experiment can be found in the appendix of [33].

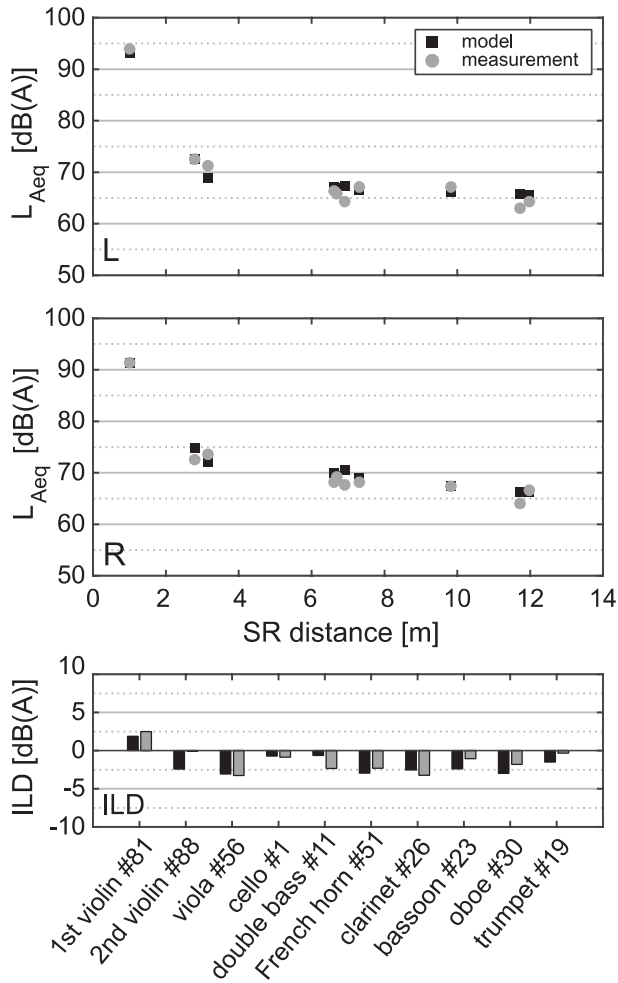


Figure 7.4. Modelled and measured sound exposure level  $L_{A,eq}$  as a result of a scale played individually by the 1st violin player 81 in MGE. Model and measurement results for the left ear (L), right ear (R) as a function of SR distance and ILD per musician. Figure 5.4 in [33].

## 7.2.4 Comparison for the symphony

The 85 bars of the Mahler piece have been divided into 46 short excerpts. An example of the  $L_{A,eq}$  per excerpt for the measured and modelled cello and trumpet is shown in Figure 7.5. The MAD in  $L_{A,eq}$  has been analysed at the 10 receiver positions in the orchestra for each hall using all excerpts (in total 46 x 10 x 3). The MAD per excerpt per hall (46 x 3), averaged over the 10 receiver positions, is within a range of 1 to 6 dB. The majority of the positions

show a MAD < 3 dB for both ears. The ILD has a deviation between model and measurement lower than 2 dB in most cases. In general, the deviations per excerpt are consistent for the three venues. This indicates that specific passages of the orchestra’s performance might consistently be interpreted differently from the player(s) in the anechoic room. Extensive results of the symphony experiment can be found in the appendix of [33].

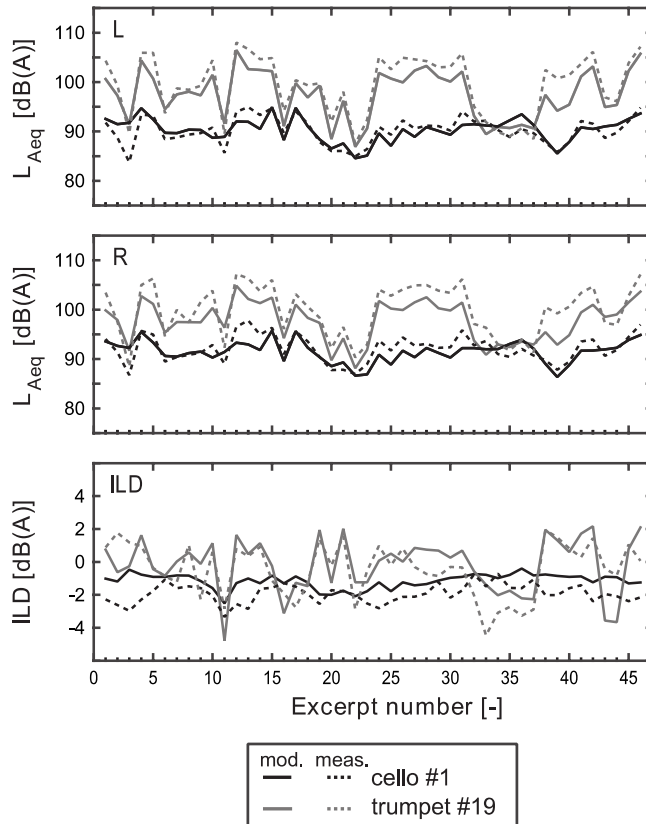


Figure 7.5.  $L_{A,eq}$  and ILD as a function of 45 excerpts for the 85 bars of the Mahler piece played in MGE. Modelled (solid) and measured (dashed) results for the cello (black) and trumpet (grey). Figure 5.10 in [33].

In order to get an overview, the  $L_{A,eq}$  per musician for the complete Mahler piece is presented in Figure 7.6. Absolute values show that the lower measured  $L_{A,eq}$  at the cello and contrabass are well predicted by the model. For 65% of the 60 microphone positions in total, the  $L_{A,eq}$  difference between the calculated and measured values is below the expected accuracy of the measurement (+/- 2 dB). The model does not structurally over- or

underestimate the sound exposure. An interesting outlier is the French horn section in MGE. Listening to the recordings reveals that they played with much more expression in this hall compared to other halls. This likely caused the 6 dB higher  $L_{A,eq}$  measured at the French horn player's ears and 3-5 dB higher levels at the right ear of close others. The prediction for ILD is mostly in line with the measurements, with the exception of the 2nd violin player whose left ear was relatively close to the instrument.

For the modelled results, both the total and the separate own instrument  $L_{A,eq}$  are presented in Figure 7.6. As expected, the contribution of the own instrument is low for the cello and contrabass. For the other players, the own instrument's  $L_{A,eq}$  is within 10 dB from the total  $L_{A,eq}$ . This indicates that both the own instrument and the other instruments influence the total sound exposure level when averaged over active and inactive periods.

The modelled results are very similar for the three different halls. The early and late reflected sound levels were almost equal and influence the model output by not more than 0.5 dB. The different orchestral layouts have a predicted influence below 1.5 dB. The larger differences found in the measurements of different venues suggest that factors not included in the model must have influenced the sound levels more. Nevertheless, in many cases the model is sufficiently accurate to predict the absolute sound levels within 2 dB with a maximum deviation of 6 dB. In the next section the model will be applied to estimate the effectiveness of sound exposure control measures. The model was validated for the prediction of absolute sound levels in the three different rooms but not validated for the configurations that are calculated in the next section. As we will see, the calculated differences are often smaller than 2 dB(A) and the question is whether such small differences can be measured significantly. A repeated measurement of the sound pressure level at positions within the orchestra, playing a 3 minute excerpt twice for the same conditions with a 15 minute coffee break in between, showed differences between 0 and 0.3 dB(A). Even though this repeatability might be low enough to measure significant sound level differences between different stage conditions, this was not further investigated in current research. Therefore, for the model, it is assumed that if it predicts differences between configurations larger than 2 dB the change in sound exposure can be considered significant, because this is the overall precision of a measurement.

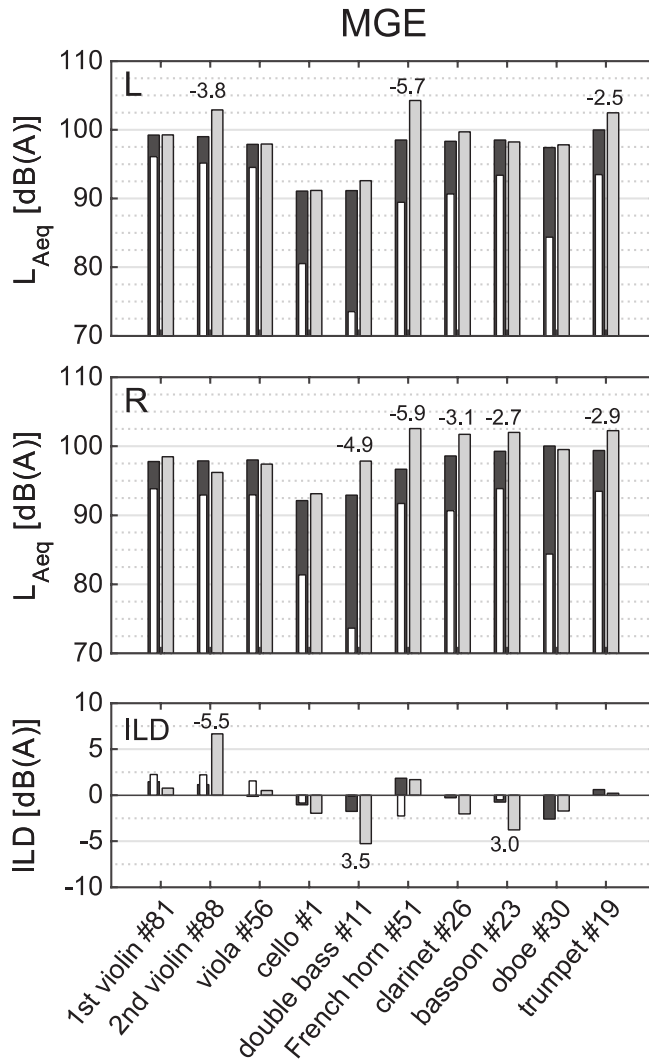


Figure 7.6a. Modelled and measured sound exposure level  $L_{A,eq}$  for the left ear (L), right ear (R) and interaural level difference (ILD) as a result of the Mahler piece modelled using anechoic recordings (Pätynen et al., 2008) and played in **MGE**. For the modelled results, both the total  $L_{A,eq}$  (dark grey) and the own instrument  $L_{A,eq}$  (white bar) are presented. Numbers indicated differences between modelled and measured results larger than 2 dB, which is the expected accuracy of a sound exposure measurement. Figure 5.14 in [33].

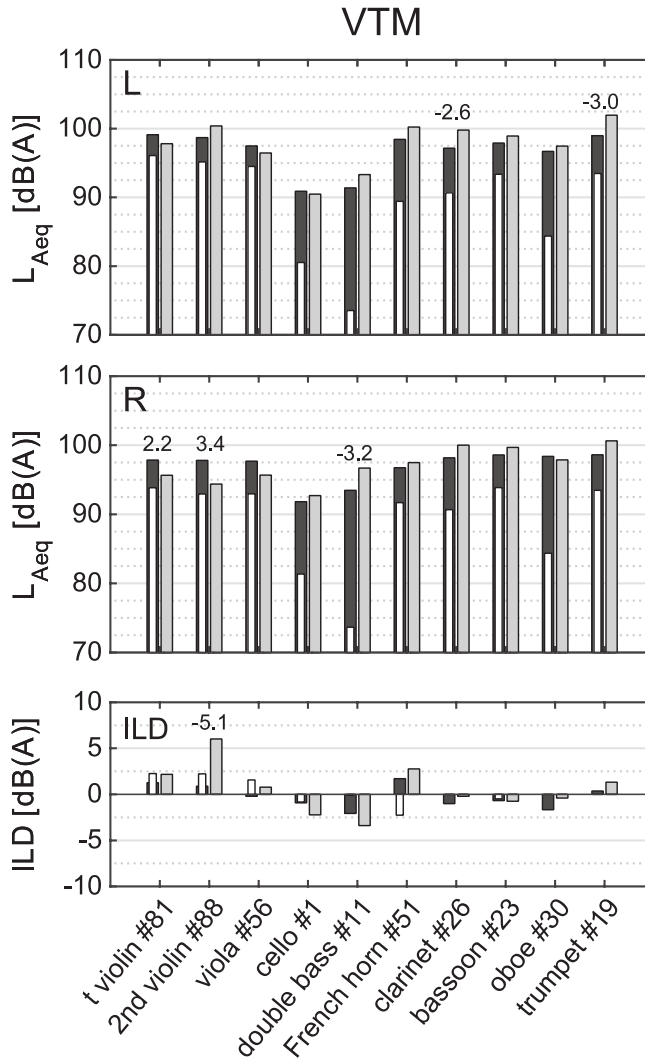


Figure 7.6b. Modelled and measured sound exposure level  $L_{A,eq}$  for the left ear (L), right ear (R) and interaural level difference (ILD) as a result of the Mahler piece modelled using anechoic recordings (Pätynen et al., 2008) and played in **VTM**. For the modelled results, both the total  $L_{A,eq}$  (dark grey) and the own instrument  $L_{A,eq}$  (white bar) are presented. Numbers indicated differences between modelled and measured results larger than 2 dB, which is the expected accuracy of a sound exposure measurement. Figure 5.14 in [33].

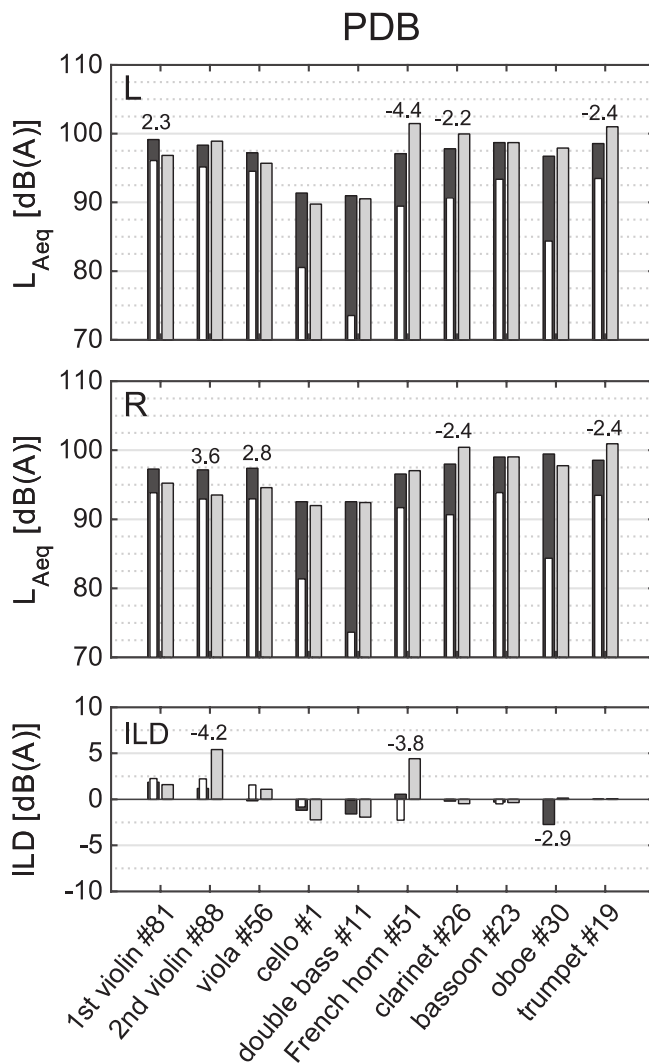


Figure 7.6c. Modelled and measured sound exposure level  $L_{A,eq}$  for the left ear (L), right ear (R) and interaural level difference (ILD) as a result of the Mahler piece modelled using anechoic recordings (Pätynen et al., 2008) and played in **PDB**. For the modelled results, both the total  $L_{A,eq}$  (dark grey) and the own instrument  $L_{A,eq}$  (white bar) are presented. Numbers indicated differences between modelled and measured results larger than 2 dB, which is the expected accuracy of a sound exposure measurement. Figure 5.14 in [33].



## 7.3 Effectiveness of control measures

### 7.3.1 Configurations

The effectiveness of a number of control measures has been investigated using the model. As a reference configuration, the concert hall model MGE is used including its orchestra layout (approximately 2 m<sup>2</sup>/musician) with risers (0.25, 0.5 and 0.75 m), see Figure 7.3, and  $ST_{early,d} = -16$  dB and  $ST_{late,d} = -18$  dB in occupied conditions. The following configurations were tested:

- To investigate the effect of available space, the orchestra layout is scaled from 2 m<sup>2</sup>/musician to 1.5 and 2.5 m<sup>2</sup>/musician.
- The effect of risers is investigated by multiplying the height by a factor of 2 and 4 and by removing the risers as a whole. This leads to a maximum height of 3 m of the brass and percussion in the last row.
- A 1 x 1 m<sup>2</sup> screen is considered that is positioned at 0.3 m behind a musician. Equal screen attenuation is assumed for those musicians in the shadow of the screen. Besides, to estimate the maximum possible reduction by screens an extreme hypothetical case is modelled as if the receivers are fully surrounded by such screens. The acoustic screening by music stands is included in the attenuation factor for sound passing through the orchestra [34] and not modelled separately.
- The acoustic properties of the room are changed by increasing the early and late reflected sound levels ( $ST_{early,d}$  and  $ST_{late,d}$ ) by +6 dB, and -6 dB to simulate relatively large acoustic interventions (+ 6 dB corresponds to a small rehearsal room < 1,000 m<sup>3</sup> and -6 dB to a dry room such as a drama theatre [34].
- The effect of rotating the position of musicians is investigated for the three spacing conditions by evaluating the variation among players within in the same strings section.

The control measures were not tested for an orchestra pit environment because the model was not validated under these conditions. The effectiveness of control measures in an orchestra pit might be different from that on an open stage.

### 7.3.2 Results and discussion

Table 7.1 shows the calculated change in sound exposure for the Mahler excerpt at ten musicians' positions in the orchestra for the different stage configurations. Results are rounded to one decimal place to be able to appreciate the small differences between musicians and between configurations. This does not necessarily reflect the accuracy of the model, which has not been validated for predicting differences in sound pressure level.

Calculated results indicate that the riser height influences the sound exposure levels by less than 0.5 dB in most cases. Changing the distance between players also has a limited influence on the calculated sound exposure with an average of +/- 0.6 dB (positive or negative sign for decrease or increase of space). Similar to the effect of risers, mostly the direct sound

level is influenced by changing the available space. The result is a maximum reduction of only 1 dB when the 95 musicians occupy 250 m<sup>2</sup> instead of 200 m<sup>2</sup>, which in practice would be a substantial increase of space.

The impact of single screens behind musicians is low, in most cases sound exposure is reduced by less than 1 dB. Only the violins' left ears and the trumpet player's ears show a higher reduction up to 1.5 dB. Drawing comparisons of results to other studies is difficult because conditions are different, such as orchestra setup, room conditions and repertoire etc. Nevertheless, our values are in line with findings by Martinez [20] showing only 1-dB reduction by a large barrier in the middle of the orchestra. The 4 to 6-dB reduction measured by O'Brien et al. [19] at a cello player in front of trumpet players might be an optimistic case where the loudest players sit behind the softest player. In the modelled orchestra, low string players sit at a larger distance from brass players reducing the impact of screens.

The calculated results for the extreme case with screens completely surrounding the musician (at only 0.3 m distance) should be interpreted with care, because the scenario is not realistic. The highest sound reduction by such screens is calculated for the woodwind and brass players with an average of 3 dB. This can be explained by the fact that their close neighbours are in total louder than the player's own instrument. Less sound reduction is calculated for the high string players with an average of 2 dB. Their own direct sound is louder compared to their close neighbours' total, which is especially the case for the left ear near the string instrument. An asymmetrical reduction is also calculated for the low strings with 1 dB on average. In this case, the louder instruments (brass) are sitting on the right side which makes screens 1 dB more effective on this side.

While surrounding screens would be most effective near the brass and woodwinds, changing room acoustic conditions is most effective for those who play softest, namely the low strings. This is because their own and their neighbours' direct sound level are relatively weak compared to the sound level of early and late reflections. Decreasing the early and late reflected sound levels by 6 dB results in an average reduction of 3 dB (left ear) and 2 dB (right ear) for the low strings. At all other instrument positions the reduction is below 1 dB.

**Table 7.1. Calculated sound exposure  $L_{A,eq}$  difference in dB for variations in riser height, musicians spacing, screening and room acoustic conditions. The reference condition shows absolute values. The other conditions show values relative to the reference condition. It should be noted that the case with screens surround is a hypothetical (unrealistic) scenario. Bold values show significant results larger than +/- 2 dB.**

- Large table on next page -

		reference model	Riser height x 2	Riser height x 4	Risers removed	1.5 m <sup>2</sup> /musician	2.5 m <sup>2</sup> /musician	screens behind	screens surround	ST <sub>early,d</sub> & ST <sub>late,d</sub> -6 dB	ST <sub>early,d</sub> & ST <sub>late,d</sub> +6 dB
<b>Conf.</b>	Space per mus.	2.0	2.0	2.0	2.0	1.5	2.5	2.0	2.0	2.0	2.0
	Riser step height	0.25	0.5	1.0	0	0.25	0.25	0.25	0.25	0.25	0.25
	Screens	No	No	No	No	No	No	Yes	Yes	No	No
	ST <sub>early,d</sub> & ST <sub>late,d</sub>	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	-6 dB	+6 dB
<b>Left</b>	1st violin #81	99.2	0.0	-0.1	0.1	0.4	-0.5	-1.1	-1.7	-0.4	1.3
	2nd violin #88	99.0	0.0	-0.1	0.0	0.5	-0.6	-1.3	<b>-2.1</b>	-0.4	1.4
	viola #56	97.9	0.0	-0.1	0.0	0.5	-0.5	-0.4	-1.5	-0.6	1.7
	violin cello #1	91.1	0.0	0.0	0.2	0.4	-0.4	-0.1	-0.3	<b>-2.8</b>	<b>4.6</b>
	double bass #11	91.2	0.0	-0.2	0.1	0.6	-0.5	-0.2	-0.6	<b>-3.0</b>	<b>4.7</b>
	French horn #51	98.5	0.0	-0.1	0.1	0.6	-0.7	-0.4	<b>-2.7</b>	-0.5	1.5
	clarinet #26	98.3	0.7	0.2	0.2	0.7	-0.6	-0.6	<b>-2.5</b>	-0.6	1.9
	bassoon #23	98.5	0.7	0.5	0.2	0.8	-0.5	-0.5	<b>-2.1</b>	-0.6	1.8
	oboe #30	97.4	-0.3	-0.6	-0.2	0.9	-0.9	-1.0	<b>-3.4</b>	-0.7	<b>2.1</b>
	trumpet #19	100.0	0.0	-0.5	-0.1	0.5	-0.5	-1.1	<b>-3.5</b>	-0.4	1.3
<b>Right</b>	1st violin	97.8	0.0	0.0	0.0	0.5	-0.4	-0.2	<b>-2.0</b>	-0.6	1.7
	2nd violin #88	97.9	0.0	0.0	0.0	0.5	-0.6	-0.3	<b>-2.5</b>	-0.6	1.7
	viola #56	98.0	0.0	-0.2	0.1	0.7	-0.7	-0.8	<b>-2.4</b>	-0.6	1.7
	violin cello #1	92.1	0.1	0.0	0.3	0.8	-0.7	-0.7	-1.0	<b>-2.0</b>	<b>3.9</b>
	double bass #11	92.9	-0.1	-0.4	0.2	0.9	-0.9	-1.1	-1.8	-1.7	<b>3.7</b>
	French horn #51	96.7	0.1	0.0	0.1	0.5	-0.5	-0.1	-1.4	-0.7	<b>2.1</b>
	clarinet #26	98.6	0.5	-0.1	0.0	0.7	-0.7	-0.3	<b>-3.2</b>	-0.6	1.8
	bassoon #23	99.3	0.6	0.1	0.1	0.6	-0.5	-0.4	<b>-2.6</b>	-0.5	1.6
	oboe #30	100.0	-0.1	-0.2	-0.1	0.6	-1.1	-0.3	<b>-5.4</b>	-0.4	1.3
	trumpet #19	99.4	0.1	-0.6	0.2	0.7	-0.6	-1.5	<b>-2.7</b>	-0.5	1.5
<b>ILD</b>	1st violin #81	1.5	0.0	0.0	0.0	-0.1	0.0	-0.9	0.3	0.2	-0.4
	2nd violin #88	1.1	0.0	0.0	0.0	0.0	0.0	-1.0	0.4	0.1	-0.3
	viola #56	-0.1	0.0	0.1	0.0	-0.3	0.2	0.3	0.9	0.0	0.0
	violin cello #1	-1.0	0.0	0.0	-0.2	-0.4	0.2	0.6	0.7	-0.8	0.7
	double bass #11	-1.8	0.1	0.2	0.0	-0.3	0.3	0.9	1.2	-1.2	1.1
	French horn #51	1.8	0.0	-0.1	0.0	0.1	-0.2	-0.3	-1.3	0.3	-0.6
	clarinet #26	-0.3	0.2	0.3	0.2	-0.1	0.1	-0.3	0.6	0.0	0.1
	bassoon #23	-0.8	0.2	0.4	0.1	0.1	0.0	-0.1	0.6	-0.1	0.2
	oboe #30	<b>-2.6</b>	-0.1	-0.4	-0.1	0.3	0.2	-0.6	1.9	-0.3	0.8
	trumpet #19	0.6	0.0	0.1	-0.3	-0.2	0.2	0.3	-0.8	0.1	-0.2

This shows that, with this common seating configuration, the direct sound levels are dominant at the ears of players of loud(er) instruments. Increasing the reflected sound levels by +6 dB (as in a small rehearsal room) results in a larger difference in sound exposure than reducing reflected sound levels -6 dB for both soft and loud instruments. For all instruments, except for low strings, the increase in total exposure is between 1.3 and 2.1 dB, which means that some musicians experience a significant increase. This shows that changing acoustic conditions only moderately affects sound exposure. Only the low strings find their exposure rise significantly by 3.7 to 4.7 dB.

In most cases, the interaural level differences (ILDs) are not significantly changed by noise control measures. An exception from the cases with screens and instruments that receive much louder direct sound from their neighbours compared to their own instrument, which are the horn player sitting in the middle of the horn section and the oboe player sitting next to the flutes.

**Table 7.2. Calculated range in sound exposure  $L_{A,eq}$  in dB over positions within the string player groups for different spacing: 1.5, 2.0 and 2.5 m<sup>2</sup> per musician. The configuration is the current concert hall condition with 0.25 m riser step height and no screens. The 1st and 2nd violins are first analysed per different part and then averaged.**

Instrument	1.5 m <sup>2</sup> /musician			2 m <sup>2</sup> /musician (ref)			2.5 m <sup>2</sup> /musician		
	Left	Right	ILD	Left	Right	ILD	Left	Right	ILD
1st violins	1.5	2.2	2.1	1.3	1.8	1.9	1.2	1.5	1.6
2nd violins	1.4	1.1	1.0	1.2	1.0	0.9	1.0	0.9	0.7
viola	1.6	1.1	0.8	1.4	1.1	0.7	1.1	1.0	0.6
cello	2.4	4.2	1.9	2.2	3.7	1.8	1.9	3.3	1.7
double bass	2.0	3.3	1.3	1.8	3.0	1.2	1.5	2.6	1.1

In order to show the effectiveness of rotating players' positions in their own instrument section, Table 7.2 presents the range in sound exposure over positions within the five strings sections. The range varies between 1.0 and 4.2 dB and is smaller when the space per musician increases. The 1st violin players with the highest exposure are located in the middle of the 1st and 2nd violin sections combined; not those positioned closer to the horns as one might expect. For the other string sections, positions closest to other louder sections are indeed exposed most. The amount of variation among high string players is below 2 dB for most cases and the effectiveness of rotating those musicians seems limited, which confirms the findings by Schmidt et al. [11]. Only for the low string players, the exposure of the right ear varies significantly when rotating.

## 7.4 Summary and conclusion

The effectiveness of common control measures to reduce sound exposure of orchestral musicians has been investigated using an acoustic prediction model. The model calculates the equivalent sound levels for a performance of the first 2 minutes of Mahler's 1st symphony part 4, which can be considered representative for loud orchestral music. Validation measurements have shown that the calculation model is able to predict the  $L_{A,eq}$  within 2 dB deviation for 65% of the investigated microphone positions, with a maximum deviation of 6 dB. It should be noted that the model does not take into account a possible different playing style under different conditions that might affect sound levels.

The 2 dB accuracy of a sound exposure measurement has been used as a limit above which control measures are judged being significantly effective. With the same amount of musicians and equal room acoustic conditions, the available space and the height of risers have only a small effect (< 1 dB) on the sound exposure of musicians in the orchestra. A slightly larger effect is obtained by introducing a sound absorbing screen closely behind a musician sitting near (many) loud players, leading to a maximum decrease of 1.5 dB. The reduction by screens that would completely surround a musician (however not realistic) varies between 0.5 dB for low strings and on average 3.4 dB for players in loud instrument sections such as brass and woodwinds. In contradiction to the effect of screens, changing the room acoustic conditions, by extremely reducing the early and late reflected sound levels, only has a significant effect for the low strings, ranging from 3.7 to 4.7 dB. For most other musicians, changing room acoustic conditions would not lead to changes in sound exposure of more than 2 dB. Similarly, rotating positions has the largest effect on exposure of low string players by 1.8-3.7 dB for typical concert hall acoustic conditions. For high string players, rotating positions has an effect less than 2 dB in most cases.

In general, it can be concluded that the calculated effectiveness of common control measures to sound exposure of musicians playing in a symphony orchestra is within a limited range of 0.5 to 5 dB and in many cases below the measurement accuracy of 2 dB. Extreme unrealistic measures are necessary to achieve the highest reductions. This conclusion confirms results from a number of studies who also found limited reduction in sound exposure, or no reduction at all, after introducing physical measures. A reduction of 3 dB could improve conditions for musicians as much as shortening their rehearsal time by a half, which means that physical measures should not be completely neglected. However, it seems impossible for physical measures to be effective enough to replace hearing protection devices such as ear plugs that can easily attenuate 20 dB or more.

Earlier research has shown that higher equivalent sound levels occur during individual rehearsal compared to group rehearsal. Therefore, most musicians are better off playing in the orchestra than rehearsing at home. Still, many musicians predominantly focus on taking measures when playing in the orchestra. It seems that professional musicians, but also active amateur musicians, playing current modern powerful instruments and music have no other choice than to protect their ears with ear plugs under all circumstances if they wish to avoid the risk of developing hearing damage.

## **7.5 Recommendations for future research**

The current study has focused on equivalent sound levels while disregarding peak sound levels which cannot be studied using the prediction model. The peak sound levels measured in symphony orchestras are mostly below the risk limit of 140 dB(C) described in the EU Directive [1, 12]. Nevertheless, peak sound levels are relatively high and should be considered in the evaluation of exposure to orchestral sound. The impact of control measures, such as screens, on peak sound levels needs further investigation. The current research could also be extended by studying the effectiveness of control measures when playing different repertoire (if available in anechoic format) and with different orchestra setups. Besides, validation measurements would be valuable to check our findings based on calculations. Such measurements would require a high precision in terms of reproducibility of the power output by actual musicians.

The effect of control measures on sound exposure could also be studied for smaller ensembles, such as chamber music ensembles, wind bands, jazz or percussion ensembles. The relative influence of the diffuse sound field sound level might be less dominant in a small ensemble because they comprise fewer players at larger distance, possibly in a room with more sound absorption. In such a scenario, screens are potentially more effective than has been shown in the present study. Nevertheless, the exposure of the own instrument will always play an important role and most instruments expose the own player considerably. This means that, even if barriers could be more effective to block the sound of others in smaller ensembles, ear plugs would always be necessary to protect the ears from the own instrument's exposure.

The model does not take into account how orchestra musicians might adjust their playing levels as a function of what (which levels) they hear from their own instrument, group or other parts of the orchestra. Also, a higher level of reflected sound energy could result in a softer playing style, as was shown for a cello soloist [41], which reduces the direct sound exposure of the own instrument. There might be a positive effect of higher reflection levels in terms of lower total exposure levels for musicians with loud instruments. More research is necessary to investigate if and how musicians adapt to their acoustic environment in an orchestra.

The conclusions in the present study should be interpreted with care for conditions different from open stages or (large) rehearsal rooms. For instance, in an orchestra pit the

effectiveness of control measures will likely be different. Nevertheless, the contribution of the sound of the own instrument to the total exposure will be substantial under all conditions. And, sound levels in orchestra pits are usually higher than in ‘open rooms’, see [13], most likely also when using control measures. Therefore, the main conclusion also applies for orchestral musicians playing in orchestra pits: ear plugs are inevitable for protecting musicians’ ears.

## 7.6 References

- [1] European Parliament and the Council of the European Union: Directive 2003/10/ec of the European parliament and of the council of 6 February 2003. Official Journal of the European Union L42 (2003) 38-44.
- [2] A. Behar, W. Wong, H. Kunov: Risk of hearing loss in orchestra musicians. *Medical Problems of Performing Artists* 4 (2006) 164-168.
- [3] J.H. Schmidt, E.R. Pedersen, H.M. Paarup, J. Christensen-Dalsgaard, T. Andersen, T. Poulsen, J. Bælum: Hearing loss in relation to sound exposure of professional symphony orchestra musicians. *Ear & Hearing* 35(4) (2014) 448-460.
- [4] H. Laitinen, T. Poulsen: Questionnaire investigation of musicians’ use of hearing protectors, self-reported hearing disorders, and their experience of their working environment. *International Journal of Audiology* 47(4) (2008) 160-168.
- [5] E.J.M. Jansen, H.W. Helleman, W.A. Dreschler, J.A.P.M. de Laat: Noise induced hearing loss and other hearing complaints among musicians of symphony orchestras. *International Archives of Occupational and Environmental Health* 82(2) (2009) 153-164.
- [6] K.R. Kähäri, A. Axelsson, P.A. Hellström, G. Zachau: Hearing assessment of classical orchestral musicians. *Scandinavian Audiology* 30(1) (2001) 13-23.
- [7] H.M. Laitinen, E.M. Toppila, P.S. Olkinuora, K. Kuisma: Sound exposure among the Finnish National Opera personnel. *Applied Occupational and Environmental Hygiene* 18(3) (2003) 177-182.
- [8] I. O’Brien, T. Driscoll, W. Williams, B. Ackermann: A clinical trial of active hearing protection for orchestral musicians. *Journal of Occupational and Environmental Hygiene* 11(7) (2014) 450-459.
- [9] J.D. Royster, L.H. Royster, M.C. Killion: Sound exposures and hearing thresholds of symphony orchestra musicians. *J. Acoust. Soc. Am.* 89(6) (1991) 2793-2803.
- [10] M.A. Rodrigues, M.A. Freitas, M.P. Neves, M.V. Silva: Evaluation of the noise exposure of symphonic orchestra musicians. *Noise & Health* 16(68) (2014) 40.
- [11] J.H. Schmidt, E.R. Pedersen, P.M. Juhl, J. Christensen-Dalsgaard, T.D. Andersen, T. Poulsen, J. Bælum: Sound exposure of symphony orchestra musicians. *Annals of Occupational Hygiene* 55(8) (2011) 893-905.
- [12] I. O’Brien, W. Wilson, A. Bradley: Nature of orchestral noise. *J. Acoust. Soc. Am.* 124(2) (2008) 926-939.
- [13] A.C. Gade: Sound levels in rehearsal and medium sized concert halls; are they too loud for the musicians? *J. Acoust. Soc. Am.* 131(4) (2012) 3243-3243.
- [14] I. O’Brien, T. Driscoll, B. Ackermann: Sound exposure of professional orchestral musicians during solitary practice. *J. Acoust. Soc. Am.* 134(4) (2013) 2748-2754.

- [15] A.C. Gade, J. Kapenekas, B.T. Andersson, J.I. Gustafsson: Acoustical problems in orchestra pits; causes and possible solutions. In 17th International Congress Acoustics Roma (2001).
- [16] J.E. Camp, S.W. Horstman: Musician sound exposure during performance of Wagner's Ring Cycle. *Medical Problems of Performing Artists* 7(2) (1992) 37-39.
- [17] W. Williams, G. Stewart: Noise exposure reduction for orchestral musicians. *Acoustics Australia* 39(2) (2011) 73-74.
- [18] R. Libera, S. Mace: Shielding sound: A study on the effectiveness of acoustic shields. *Journal of Band Research* 45(2) (2010) 23-41.
- [19] I. O'Brien, J. Wood, B. Ackermann: Assessment of an acoustic screen used for sound exposure management in a professional orchestra. *Acoustics Australia* 41(2), 146 (2013).
- [20] C.Z. Martinez: The effect of acoustic screens on orchestra musicians. Bachelor Thesis, Hochschule für Musik Detmold (2012).
- [21] M. Chasin: *Hear the music: Hearing loss prevention for musicians*. Canada: Author.
- [22] S. Eaton, H. Gillis: Review of orchestra musicians' hearing loss risks," *Canadian Acoustics* 30(2) (2002) 5-12.
- [23] H.P. Tennhardt, H. Winkler: Studies on the acoustical planning of orchestral practice rooms. *Acta Acust. Acust.* 81(4) (1995) 293-299.
- [24] R. Pompoli, N. Prodi, A. Farnetani: A note on the acoustics of orchestra rehearsal rooms. *Building Acoustics* 19(1) (2012) 1-11.
- [25] R.H.C. Wenmaekers, L.J. Schmitz, C.C.J.M. Hak: Early and late support over various distances-rehearsal rooms for wind orchestras. *Proceedings of Forum Acusticum Krakow* (2014).
- [26] J.H. Rindel: New Norwegian standard on the acoustics of rooms for music rehearsal and performance. *Proceedings of Forum Acusticum Krakow* (2014).
- [27] M. Lautenbach, M. Vercammen: Stage acoustic requirements extended to orchestra rehearsal rooms. *Proceedings of ISMRA 2016*.
- [28] H. Laitinen: Factors affecting the use of hearing protectors among classical music players. *Noise & Health* 7(26) (2005) 21-29.
- [29] I. O'Brien, B.J. Ackermann, T. Driscoll: Hearing and hearing conservation practices among Australia's professional orchestral musicians. *Noise & Health* 16(70) (2014) 189-195.
- [30] K. Chesky, M. Pair, E. Yoshimura, S. Landford: An evaluation of musician earplugs with college music students. *International Journal of Audiology* 48:9 (2009) 661-670.
- [31] E.F. Beach, I. O'Brien: In their own words: interviews with musicians reveal the advantages and disadvantages of wearing earplugs. *Medical Problems of Performing Artists* 32(2) (2017) 101-110.
- [32] R.H.C. Wenmaekers, C.C.J.M. Hak: A sound level distribution model for symphony orchestras: Possibilities and limitations. *Psychomusicology: Music, Mind, and Brain* 25(3) (2015) 219-233.
- [33] B. Nicolai: The influence of stage acoustics on sound exposure of symphony orchestra musicians. Master Thesis. Eindhoven University of Technology (2016). Available via [www.researchgate.net/profile/Remy\\_Wenmaekers](http://www.researchgate.net/profile/Remy_Wenmaekers).
- [34] R.H.C. Wenmaekers, C.C.J.M. Hak, M.C.J. Hornikx: How orchestra members attenuate direct, early reflected and late reflected sound on five different concert stages and orchestra pits. *J. Acoust. Soc. Am.* 140(6) (2016) 4437-4448.



- [35] A.C. Gade: Investigations of musicians' room acoustic conditions in concert halls. *Acustica* 69 (1989) 193-203 & 249-261.
- [36] R.H.C. Wenmaekers, C.C.J.M. Hak, L.C.J. van Luxemburg: On measurements of stage acoustic parameters: time interval limits and various source-receiver distances. *Acta Acust. Acust.* 98(5) (2012) 776-789.
- [37] R.H.C. Wenmaekers, C.C.J.M. Hak: The sound power as a reference for sound strength (G), speech level (L) and support (ST): Uncertainty of laboratory and in-situ calibration. *Acta Acust. Acust.* 101(5) (2015) 892-907.
- [38] R.H.C. Wenmaekers, C.C.J.M. Hak, M.C.J. Hornikx, A.G. Kohlrausch: Sensitivity of stage acoustic parameters to source and receiver directivity: Measurements on three stages and in two orchestra pits. *Appl. Acoust.* 123 (2017) 20-28.
- [39] J. Pätynen, V. Pulkki, T. Lokki: Anechoic recording system for symphony orchestra. *Acta Acust. Acust.* 94(6) (2008) 856-865.
- [40] IEC 61672-1. Electroacoustics-Sound level meters-Part 1: Specifications (2002).
- [41] Z. Schärer Kalkandjiev, S. Weinzierl: The influence of room acoustics on solo music performance: An empirical case study," *Acta Acust. Acust.* 99(3) (2013) 433-441.