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Sound Exposure of Symphony Orchestra Musicians

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Background: Assessment of sound exposure by noise dosimetry can be challenging especially when measuring the exposure of classical orchestra musicians where sound originate from many different instruments. A new measurement method of bilateral sound exposure of classical musicians was developed and used to characterize sound exposure of the left and right ear simultaneously in two different symphony orchestras.

Objectives: To measure binaural sound exposure of professional classical musicians and to identify possible exposure risk factors of specific musicians.

Methods: Sound exposure was measured with microphones mounted on the musician's ears and recorded digitally. The recorded sound was analysed and the specific sound exposure of the left and the right ear was determined for the musicians. A total of 114 measurements covering 106 h were recorded in two symphony orchestras.

Results: Sound exposure depends significantly on the specific instrument and the repertoire played by the exposed musician. Concerts, group rehearsals and individual practice were all significant contributors to the sound exposure. The highest L_{Aeq} of 86 –98 dB was found among the brass players. High string players were exposed from 82 to 98 dBA and their left ear was exposed 4.6 dB more than the right ear. Percussionists were exposed to high sound peaks >115 dBC but less continuous sound exposure was observed in this group. Musicians were exposed up to L_{Aeq8h} of 92 dB and a majority of musicians were exposed to sound levels exceeding L_{Aeq8h} of 85 dB.

Conclusions: Binaural recording of the individual sound exposure showed that orchestra musicians could be exposed differently to the left and right ear and that they were primarily exposed from their own instruments. Specific repertoires as well as the specific instrument determine the level of exposure.

Keywords: hearing loss; noise dosimetry; noise exposure; noise measurement; orchestral musicians

INTRODUCTION

In recent years, increasing attention regarding noise exposure at workplaces has been directed towards

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the entertainment industry including musicians. Exposures to noise at workplaces are usually controlled by national occupational health regulations that apply to all employees (Occupational Safety and Health Standards, 1971; The European Parliament and the Council of the European Union, 2003). Since damaging sound is normally regarded as unpleasant and uncomfortable sound (Daniel, 2007), sounds produced by musicians have been difficult to regard as potentially damaging. However, high sound pressure levels (SPLs) produced as music may be damaging to hearing as well.

High and potentially damaging SPLs have been reported for both classical and non-classical musicians (Obeling and Poulsen, 1999; Kähäri *et al.*, 2003; Laitinen *et al.*, 2003; O'Brien *et al.*, 2008; Zhao *et al.*, 2010). Previous studies often find the highest exposure levels among the trumpet players. It is not unusual to find an equivalent continuous sound level (L_{Aeq}) of 93–98 dB for several rehearsal hours (McBride *et al.*, 1992; Obeling and Poulsen, 1999; Lee *et al.*, 2005). In most countries, the equivalent continuous noise exposure limit for an 8-h working day (L_{Aeq8h}) is set to 85 or 90 dB (Occupational Safety and Health Standards, 1971; The European Parliament and the Council of the European Union, 2003). Furthermore, musicians only use hearing protection on rare occasions, mainly because they find it difficult to perform optimally when wearing hearing protection (Laitinen and Poulsen, 2008). Many musicians report hearing problems as well as hearing-related problems such as tinnitus or hyperacusis (Jansen *et al.*, 2009; Toppila *et al.*, 2011). Studies on musicians' risk of developing hearing loss are not conclusive. Some of the studies show that musicians are at risk of developing hearing loss (Westmore and Eversden, 1981; Jansen *et al.*, 2009). Other studies show no major risk for musicians of developing hearing loss (Obeling and Poulsen, 1999; Kähäri *et al.*, 2001a,b).

To estimate the total sound exposure of a musician, a thorough evaluation of the different work tasks must be done as they may be exposed differently during performances, rehearsals, and individual practice (Laitinen *et al.*, 2003; O'Brien *et al.*, 2008; Nielsen *et al.*, 2010).The repertoire has a considerable impact as well as the physical setup of the orchestra and the acoustic environment (Boasson, 2002; Laitinen *et al.*, 2003; Lee *et al.*, 2005; MacDonald *et al.*, 2008). Exposure at different working days with different tasks can be estimated with personal worn dosimeters (ISO 9612, 2009). Furthermore, the standard ISO 9612 specifies criteria for positioning of measurement microphones. However, there is always a risk that measurements are not representative. Classical music varies considerably in average SPLs and even within the same piece of music large fluctuations occur.

In this study, the sound measurement procedure was based on digital recording of the entire sound exposure from concerts and rehearsals. This is in contrast to the commonly used noise dosimeters, which use data logging of measurements at certain time points. The purpose was to measure the complete exposure of both left and right ear simultaneously on a number of musicians in a symphony orchestra. The procedure allowed measurement of any difference in sound exposure of the two ears.

MATERIALS AND METHODS

Measurements were made during group rehearsals and concerts on orchestral stages in two different symphony orchestras [Orchestras I (73 musicians) and II (110 musicians)]. The repertoires change every week and certain weeks in the two orchestras were chosen as measurement periods. Measurements in both orchestras were simultaneously done on several musicians in different instrument groups. The measurements lasted typically between 30 and 90 min. Besides, a limited number of measurements were also taken during individual rehearsals. The investigation resulted in a total of 228 measurements including 114 left and 114 right ear measurements covering a total of 106 h from 54 different musicians. Each musician was measured between one and seven times during different repertoires. Sixty-two measurements were from Orchestra I and 52 measurements from Orchestra II. All measurements were made in the period January to June 2010.

Personal sound exposure assessment

Two miniature microphones (DPA-4063) were used. The microphones were positioned 1–2 cm lateral to the entrance of the ear canal of the left and the right ear of the musician using custom-made ear holders. The microphones were connected to a DPA-MPS6030 battery-driven power supply and connected to an Olympus LS-10 stereo digital recorder. The microphone signals were sampled at 44.1 kHz/16 bit in uncompressed wav format. The record level was locked allowing a maximum record level of 138 dB with a dynamic range of 98 dB leaving a minimum signal of 40 dB, which was above the equivalent noise level of 26 dB of the microphone.

Each microphone was calibrated by recording a 1000 Hz reference tone at a SPL of 94 dB from a B&K type 4231 sound calibrator. Linearity of the record level was checked by comparing a 94 dB SPL to a 114 dB SPL calibration tone also generated by the B&K type 4231 sound calibrator. After recording from a musician, the sound exposure was calculated using customized MATLAB scripts. The scripts integrated and analysed the recorded sound over time from each ear of the musician as stated in equation (1).

$$L\text{Aeq}, T = 10\log_{10}\left(\frac{1}{T}\int_0^T \frac{p_A(t)^2}{p_0^2}dt + \text{correction}\right), \quad (1)$$

where $L_{\text{Aeq},T}$ is the A-weighted SPL recorded at the musician's ear in a specific period of time (T). p_{A} is the measured SPL at a given time (t). p_0 is the reference sound pressure (20 µPa). A general correction was calculated from the recorded reference tone in order to obtain a level of 94 dB.

Maximum peak levels were calculated as C-weighted SPLs during the measurement period. The maximum peak value was found by searching the entire signal for the maximum numerical sample value. Furthermore, the number of peak values exceeding 115 dBC was counted. If more than one peak was observed within 1 s, only the largest peak was counted. All counted peaks were checked manually and artefacts (e.g. unintended contact with the measurement microphone) were excluded.

Nine measurements were made to illustrate measurement differences from the influence of microphone placement, type of microphone, and measurement method. The musicians were fitted with a B&K Noise dosimeter type 4436 as well as the miniature microphones, giving three simultaneous measurement positions. The dosimeter was calibrated with a B&K type 4231 sound calibrator prior to each measurement. The microphone of the dosimeter was mounted on the shoulder ~10 cm from the entrance of the ear canal of the apparently most exposed ear, according to ISO 9612. The average measurement difference between the microphone on the most exposed shoulder and the nearest ear microphone were then calculated to be +0.6 dB (SD 1.6 dB). Four measurements showed higher levels with the dosimeter and five measurements gave higher levels with the ear microphone. There was a tendency for the dosimeter to report higher peak values compared to the miniature microphone.

Repertoire and exposure types

During two different weeks, the orchestras played the following repertoire both at rehearsal and in concerts. Orchestra I played three musical pieces: Niels W. Gade, Ossian Overture; Dimitrij Sjostakovitj, Violin concerto No. 1; and Carl Nielsen, Symphony No. 3. Orchestra II played one musical piece: Mahler, Symphony No. 6. A limited number of measurements were also taken from Orchestra II playing Schumann, Faust.

Musicians placed at less exposed positions were registered and the less exposed positions were defined as positions without any neighbour musician to one of the two sides. There was no use of sound screens near the measured musicians. The contribution from the musician's own instrument (direct exposure) and the contribution from other musicians (indirect exposure) were evaluated in selected measurement periods. Two to six different instruments were timewise aligned and active or inactive periods of playing for minimum 90 s were identified and coded as active or inactive. Furthermore, it was coded if musicians were indirectly exposed from active neighbour musicians next to or in front/behind of them. Twenty-eight different time periods were selected from the total number of measurements.

Statistics

A linear mixed-effects model of repeated measurements was applied to model the data using the individual musicians as random effect. This statistical model could predict the most probable L_{Aeq} in the different instrument groups. The following explanatory fixed effects were used: repertoire, the instrument, musician at a less exposed position, concert, or group rehearsal. To test the sound exposure difference between the left and right ear with respect to the different instruments, the interaction term (instrument × ear) was included as explanatory variable as well. Direct versus indirect exposure was analysed using the same linear model with some adjustments. L_{Aeq} of the selected measurement period was the dependent variable and instrument type, indirect/direct exposure, active neighbour, measurement session, instrument, and left/right ear were explanatory variables. The interaction products instrument × (direct/indirect) and instrument × ear were included in the model to test the direct and indirect exposure difference of a single instrument. Data were processed using command xtmixed in STATA ver. 10.1 (Stata Corp., College Station, TX, USA).

Sound mapping

The predicted instrument-specific L_{Aeq} coefficients from the linear mixed-effects model was used to estimate a sound map of the sound exposure in the two symphony orchestras. The three different repertoires for Orchestra I were all included in Map I to reflect the overall exposure. The Map II for Orchestra II included the Mahler No. 6 symphony. The model predicted the probable sound exposure for a specific instrument group during the entire repertoire-specific period.

RESULTS

The sound exposure was evaluated during the rehearsals and concerts for Orchestras I and II. Table 1 lists L_{Aeq} throughout the entire measurement periods from all instruments measured. The high strings (first violin, second violin, and viola) were exposed up to 95–98 dB on their left side and up to 89–92 dB on the right side. The largest interaural exposure difference was found in first violins and violas, whereas the difference was smaller for the second violinists. The lowest exposure was up to L_{Aeq} of 88–89 dB found among the low strings (double bass and cello). The exposure was 1–2 dB larger on the right side reflecting an exposure directly from the brass players. Brass players were exposed between L_{Aeq} of 86–98 dB of which the trumpets consistently were above L_{Aeq} of 93 dB. Timpani players were exposed to 89–90 dBA. The exposure of the woodwinds was between 80 and 97 dBA. The flute and the bassoon had a small asymmetry in exposure with 1–2 dB higher exposure to the right ear.

Table 2 shows the measured range of peak values. The number of peaks per minute exceeding 115 dBC for the different instruments is listed in Table 3. The maximum peak values were almost identical for the different high string instruments. Violas and second violins were more frequently exposed to peak values exceeding 115 dBC. The maximum peak values measured at the low strings were 124 dBC and peaks only exceeded 115 dBC on rare occasions. The maximum peaks in the brass section were measured to 133 dBC and the peaks exceeded 115 dBC more frequently compared to the other instruments (Table 3). Timpani players were measured with peaks up to 132 dBC. High peak values of 132 dBC originated from the percussion and exposed the celesta as well. Peak values of 131 and 128 dBC were measured for the flute and the bassoon and less for the other woodwinds (122–123 dBC). Peaks were less frequent among the woodwinds compared to the left ear of second violins and violas although the woodwinds were positioned closer to the brass section (Table 3).

Figure 1 illustrates the variation in sound exposure for different musicians during individual practice. Results from measurements are shown in Table 4. The exposure during individual practice was for most instruments identical or possibly higher compared to exposure at group rehearsals. During individual practice, the left ear was exposed more than the right ear in the violinist and the trombonist and the exposure of the right ear was largest in the

Table 1. Average L_{Aeq} levels for the left and the right ear in different instrument groups. Average over all measurements in Orchestra I and Orchestra II. Number of measurements in the last column with the number of different measured musicians in parenthesis

Instrument	Left ear (dBA)				Right ear (dBA)				Number of measurements (number of musicians)
	Maximum	Minimum	SD	Mean	Maximum	Minimum	SD	Mean	Total
First violin	96.0	82.5	4.1	89.8	88.9	79.2	3.3	84.5	11 (6)
Second violin	95.4	84.8	3.7	90.9	92.7	82.2	3.3	87.3	19 (9)
Viola	98.6	82.5	5.2	92.8	90.2	82.1	2.8	86.0	8 (3)
Cello	87.1	79.4	3.9	83.4	89.5	81.5	4.0	85.5	3 (2)
Double bass	86.1	82.5	1.8	84.4	88.1	84.5	1.8	86.3	3 (2)
Flute/piccolo	95.4	88.5	2.5	92.7	97.6	85.0	3.9	93.1	8 (3)
Oboe	90.8	88.5	1.6	89.7	91.9	91.8	0.1	91.9	2 (2)
Clarinet	93.2	90.2	1.2	91.6	93.4	88.0	2.0	90.5	5 (3)
Bassoon	93.3	80.8	3.3	89.5	96.7	83.6	3.2	91.1	18 (6)
French horn	97.8	86.8	3.4	93.7	97.3	91.0	2.0	94.0	13 (7)
Trumpet	98.0	93.7	1.3	95.9	96.4	94.6	0.8	95.8	7 (4)
Trombone	96.6	88.6	2.6	93.6	95.4	88.3	2.6	92.1	12 (4)
Tuba	90.0	90.0	—	90	91.0	91.0	—	91	1 (1)
Timpani	90.7	90.3	0.3	90.5	90.3	89.3	0.7	89.8	2 (1)
Celeste	94.0	92.9	0.8	93.5	90.9	89.1	1.3	90	2 (1)

Table 2. Peak SPLs in dBC in different instrument groups for the left and right ear. Results are based on all measurements in both orchestras. Number of measurements in the last column with the number of different measured musicians in parenthesis

Instrument	Left ear (dBC)				Right ear (dBC)				Number of measurements (number of musicians)
	Maximum	Minimum	SD	Mean	Maximum	Minimum	SD	Mean	Total
First violin	128.6	116.1	4.1	121.1	122.3	110.8	3.4	114.4	11 (6)
Second violin	127.5	116.2	3.1	121.1	123.4	113.7	3.0	117.9	19 (9)
Viola	126.7	117.8	2.9	123.8	116.7	113.0	1.4	115.2	8 (3)
Cello	121.1	112.1	4.6	116	124.1	113.5	5.9	117.3	3 (2)
Double bass	114.6	112.3	1.2	113.2	116.0	111.1	2.5	113.8	3 (2)
Flute/piccolo	131.2	116.5	4.8	122.1	130.2	118.6	4.4	123.3	8 (3)
Oboe	121.4	119.4	1.1	120.7	122.4	120.4	1.1	121.4	2 (2)
Clarinet	123.2	120.4	1.1	122.0	123.4	117.9	2.1	120.9	5 (3)
Bassoon	125.2	109.7	3.2	121.6	128.0	112.7	3.3	123.1	18 (6)
French horn	132.2	116.7	6.2	124.5	132.9	119.5	5.2	125.3	13 (7)
Trumpet	132.7	119.3	4.8	125.5	133.1	122.5	4.8	126.4	7 (4)
Trombone	126.2	121.1	1.5	123.6	125.3	119.1	2.0	122.1	12 (4)
Tuba	124.2	124.2	–	124.2	123.5	123.5	–	123.5	1 (1)
Timpani	132.1	131.8	0.2	132.0	132.5	131.6	0.6	132.1	2 (1)
Celeste	132.9	123.6	6.6	128.3	133.7	118.6	10.7	126.2	2 (1)

Table 3. Average number of peaks per minute. Average over all measurements in both orchestras. Number of measurements in the last column with the number of different measured musicians in parenthesis

Instrument	Left ear				Right ear				Number of measurements (number of musicians)
	Maximum	Minimum	SD	Mean	Maximum	Minimum	Mean	SD	Total
First violin	2.0	0.1	0.8	0.8	0.80	0.0	0.3	0.3	11 (6)
Second violin	3.5	0.1	1.2	1.3	1.4	0.0	0.2	0.3	19 (9)
Viola	6.3	0.8	2.1	3.2	2.3	0.0	0.3	0.8	8 (3)
Cello	0.1	0.0	0.0	0.0	1.3	0.0	0.4	0.7	3 (2)
Double bass	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.5	3 (2)
Flute/piccolo	2.7	0.2	1.0	1.4	2.7	0.3	1.2	0.7	8 (3)
Oboe	1.2	0.1	0.8	0.7	1.0	0.7	0.8	0.2	2 (2)
Clarinet	1.7	0.6	0.4	1.1	1.7	0.1	1.0	0.7	5 (3)
Bassoon	5.1	0.3	1.3	1.7	4.1	0.5	1.9	1.2	18 (6)
French horn	6.3	0.3	2.1	2.9	6.4	1.0	3.1	1.7	13 (7)
Trumpet	5.8	2.4	1.3	3.8	5.8	2.4	4.0	1.2	7 (4)
Trombone	5.4	1.3	1.5	3.1	4.8	0.7	2.4	1.5	12 (4)
Tuba	2.2	2.2		2.2	2.2	2.2	2.2		1 (1)
Timpani	2.5	2.3	0.2	2.4	2.4	2.3	2.4	0.1	2 (1)
Celeste	2.6	1.8	0.5	2.2	0.6	0.6	0.6	0.1	2 (1)

piccolo flutist. In particular, the flutist had a very high exposure of 104 dBA to the right ear. The continuous play during individual practice was the main cause of a higher exposure compared to group rehearsals.

Table 5 lists the coefficients obtained from the linear mixed-effects model. All coefficients were analysed by comparison to a reference situation, which was defined as a rehearsal of a reference repertoire. The reference repertoire was for the Map I model, the whole programme of Orchestra 1 and the reference repertoire used in the Map II model was Gades Ossian Overture. The mixed-effects model used all obtained measurements and predicted the

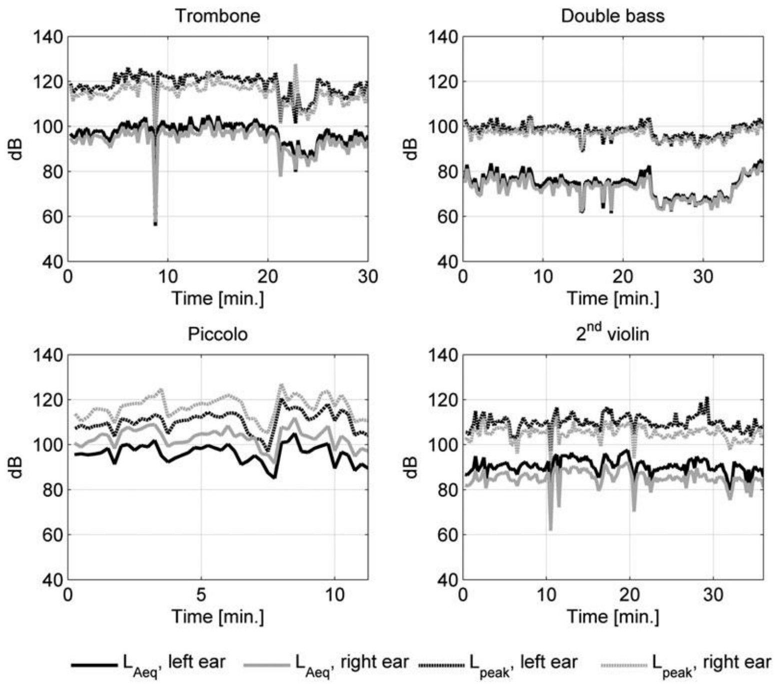

Fig. 1. Four examples of individual rehearsals. Variation in L_{Aeq} and L_{peak} during a period of individual rehearsal.

Table 4. Measurements of equivalent sound exposure (L_{Aeq}) and maximum peak value (dB_{peak}) through the entire measurement period of individual rehearsals. Trombones 1 and 2 were two different trombonists. Trombone 2 did a rehearsal in his own rehearsal room at home whereas Trombone 1 was measured in a rehearsal room at the concert hall. They were playing different repertoires. The trombonist playing trombone 2 played the quieter baroque trombone as well

Instrument	L_{Aeq} left (dB)	L_{Aeq} right (dB)	dB_{peak} left (dB)	dB_{peak} right (dB)	Period (min)
Bassoon	87.9	88.9	112.7	114.9	50.5
Double bass	76.4	74.8	104.4	102.9	38
Flute	92.1	99.5	109.2	120.6	15.75
Piccolo flute	97.8	104.5	120.5	127.0	11.75
Trombone 1	91.1	87.3	121.4	114.5	8
Trombone 2	98.9	96.2	126.2	127.2	30.5
Barok trombone	88.4	88.2	114.4	115.0	30.0
Trumpet	91.6	90.2	111.6	113.3	26.75
Viola	94.2	86.7	116.9	108.9	8.5
Second violin	91.6	86.3	121.3	112.4	36.5

most probable sound exposure for each instrument in different situations such as rehearsal or concerts and during specific repertoires. The coefficients were used to model the sound maps shown in Fig. 2. For example, the Map II column shows that a flute playing Mahler symphony No. 6 will be exposed on the left ear with the instrument-specific coefficient of 93.1 dBA + the repertoire-specific coefficient for Mahler (0.8 dB). Thus, the predicted exposure for the flute is 93.9 dBA. The repertoire-specific coefficient for Mahler symphony No. 6 indicated that all musicians during rehearsal on average are exposed 0.8 dB more than musicians playing the reference repertoire Gades Ossian Overture. Instrument-specific coefficients from Orchestras I and II in Table 5 were shown to be a good approximation of mean values of the measurements as shown in Table 1. Coefficients of Orchestra II were higher compared to mean values in Table 1. This was expected as Mahler symphony No. 6 gave higher exposure compared to the reference repertoire.

The sound exposure of symphony orchestra musicians was dependent on the actual instrument of the musician, which can be illustrated with the high strings. Sound exposure of high strings from other instruments reach both ears but the exposure of the left side is remarkably elevated due to the musician's own instrument.

The different repertoires all gave significantly different sound exposure (Table 5). The difference between Sjostakovitj and Carl Nielsen was 6.3 dB on

Table 5. Linear mixed-effects models of the effect of instrument type and type of performance. The two mixed models representing Maps I (Orchestra I) and II (Orcehstra II) are slightly different. The coefficients listed under Maps I and II refer to a reference with the coefficient 0 which is Niels W. Gades Ossian Ouverture. In case of Map I, all three repertoires of Orchestra I is regarded as one repertoire with the coefficient 0 to produce one single map from each ear of Orchestra I. Positive coefficients reflects a higher exposure from the repertoire compared to the reference repertoire. Mahler No. 6* is a special situation of Mahler No. 6 without the participation of percussion and brass wind instruments. Concert/rehearsal is with reference to rehearsal, outer position/inner position is with reference to inner position. Coefficients for instruments refer to the reference repertoire. Tuba and Celeste were not measured in Orchestra I

Exposure	Coefficient Map I (dBA)		95% CI Map I (dBA)		Coefficient Map II (dBA)		95% CI Map II (dBA)	
	Left	Right	Left	Right	Left	Right	Left	Right
Performances with reference to Niels W Gade Ossian Overture								
Sjostakovitj violin No. 1	—				−4.0		−4.7 to −3.2	
Carl Nielsen No. 3	—				2.3		1.6 to 3.0	
Mahler No. 6	1.3		0.3 to 2.3		0.8		−0.0 to 1.7	
Mahler No. 6*	−6.5		−8.4 to −4.6		−7.3		−8.7 to −6.0	
Schumann Faust	−3.5		−5.4 to −1.6		−3.7		−5.2 to −2.2	
Concert/rehearsal	1.2		0.3 to 2.1		1.0		0.4 to 1.6	
Outer/inner position	−1.9		−3.2 to −0.5		−2.0		−2.9 to −1.1	
First violin	90.9	86.0	87.1–94.1	81.7–90.4	91.7	87.0	88.9–94.5	84.1–89.9
Second violin	90.2	86.5	86.5–93.9	82.5–90.9	91.5	88.0	88.6–94.6	85.3–90.3
Viola	93.2	86.5	89.2–97.2	82.1–90.8	94.7	88.1	91.8–97.7	85.2–90.9
Cello	83.4	84.2	79.1–87.7	79.2–89.3	85.2	86.1	82.1–88.2	82.9–89.5
Double bass	85.9	85.9	82.4–89.5	82.1–89.7	85.3	85.2	82.8–87.9	82.6–87.7
Flute	92.0	93.3	88.0–95.9	88.7–98.0	93.1	94.6	90.2–96.0	91.5–97.6
Oboe	89.3	90.5	84.6–94.0	84.9–96.2	88.6	89.9	85.2–91.9	86.2–93.6
Clarinet	91.2	91.2	87.0–95.4	86.2–96.2	91.6	91.8	88.6–94.6	88.5–95.1
Bassoon	90.2	91.4	86.5–93.8	87.4–95.4	90.4	91.7	87.7–93.1	89.1–94.3
French horn	93.3	93.3	89.6–96.9	89.2–97.3	93.5	93.6	90.9–96.2	90.9–96.3
Trumpet	95.1	95.0	91.2–99.1	90.5–99.5	94.7	94.7	91.8–97.8	91.8–97.6
Trombone	93.5	91.9	89.7–97.3	87.9–96.1	93.1	91.7	90.3–95.9	88.9–94.4
Tuba					91.1	90.2	87.0–95.3	85.5–94.9
Timpani	91.1	88.5	86.1–96.0	82.9–94.4	91.6	89.0	88.0–95.2	85.3–92.7
Celeste					94.6	91.2	91.0–98.2	87.5–95.0
SD (constant)	1.0		0.6–1.7		0.8		0.6–1.2	
SD (residual)	2.2		2.0–2.5		1.5		1.3–1.6	

average of all instruments. An even lower exposure was seen during a special rehearsal of Mahler symphony No. 6 where percussion and brass players were not present. The difference of all coefficients describing the repertoire varied from −7.3 to 2.3 dB with a mean of −2.0 dB (SD 3.6 dB). Concerts gave 1–1.2 dB larger exposure than rehearsals. If the musician was seated next to an empty space, the exposure was reduced by 1.9–2.0 dB on the less exposed side. No statistical difference in exposure between musicians within identical instrument groups with respect to their position could be observed. One French horn player and one bassoonist were measured twice during the two concerts with Mahler symphony No.6 to test the measurement uncertainty. The two concerts gave almost identical sound exposure. Four measurements from the left and right ear gave a maximum difference of 1.6 dB and an average difference of only 0.7 dB.

Figure 2A and B illustrates the most likely SPL in the different instrument sections in Orchestra I based on the Map I linear mixed model. The sound maps in Fig. 2A (left ear) and Fig. 2B (right ear) are the results from the sound exposure of a typical musician playing the entire concert.

In Fig. 2C (left ear) and Fig. 2D (right ear), the most likely exposure of the different instrument groups are illustrated for Orchestra II during rehearsals and concerts of Mahler symphony No. 6. From Fig. 2, it is seen that the sound exposure of the left

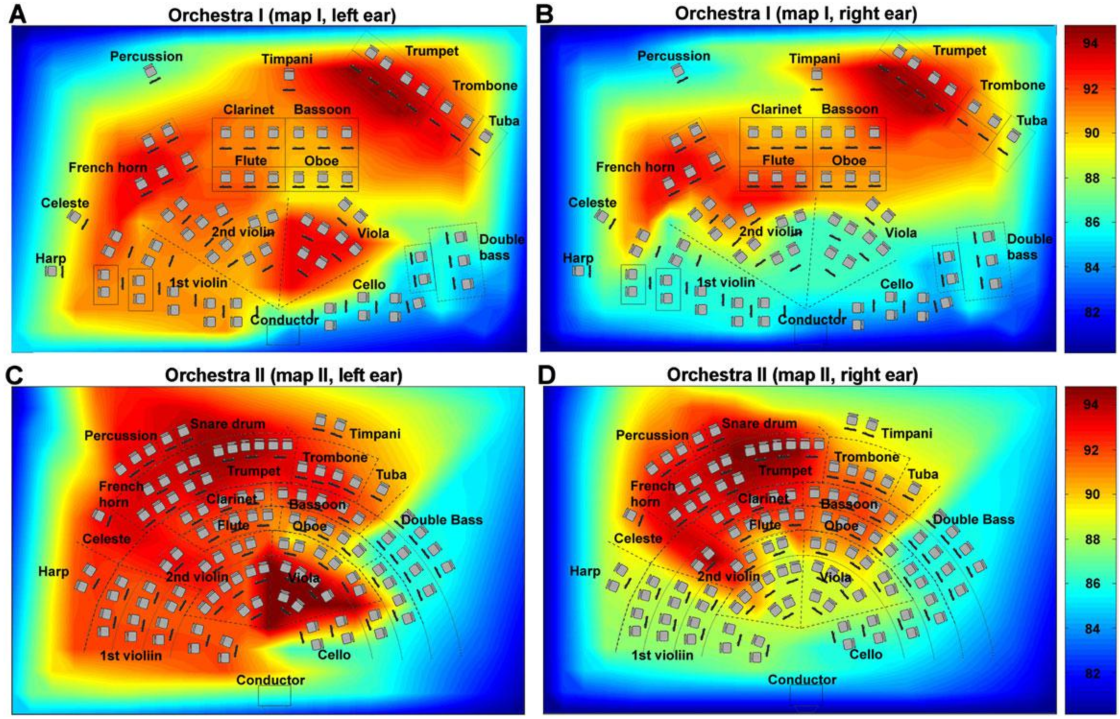

Fig. 2. (A–D) Sound maps for left and right ear exposure of musicians in Orchestra I (A + B) and Orchestra II (C + D). Coefficients to produce Map I are derived from Table 4 (Map I). Coefficients to produce Map II are derived from Table 4 (Map II). In case of Map II, the values have been added 0.8 dB, which is the repertoire-specific constant of Mahler No.6, the repertoire illustrated in Map II.

and right ear is different. The differences vary between the different instruments in the orchestra. It is noticeable that the SPL describing the viola is high on the left ear. Six different measurements on different days on one viola player all resulted in high exposure and the model is influenced by the measurement from this particular player. A loud playing style or a close positioning of his head with the microphone towards the instrument may be the reason. An analysis without that particular viola player reduces the predicted exposure of the left ear to 91.3 dBA and to 86.2 dBA for the right ear of the viola for Map I and to 93.6 dBA and 88.7 dBA, respectively, for Map II.

To investigate the asymmetric exposure, the interaction term (instrument × ear) was included in the model. It revealed a difference of 4.6 dB [confidence interval (95% CI) 3.9–5.3 dB, $P < 0.001$] in the exposure between the left and right ear for the high strings. Woodwinds had a small −1.1 dB asymmetric exposure highest at the right ear (95% CI −0.4 to −1.8 dB, $P < 0.004$), while no significant difference in exposure between the left and the right ear was seen for low strings and brass players. Exposure

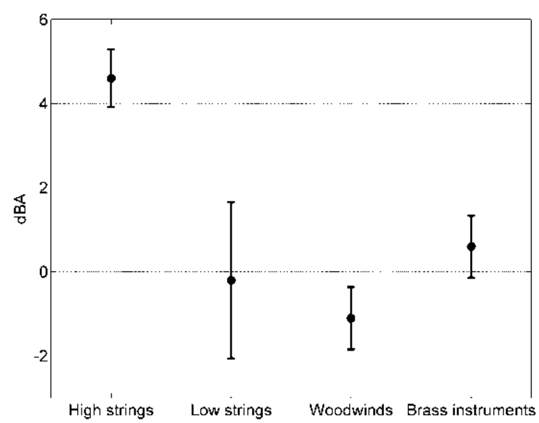

Fig. 3. Difference in exposure between the left and the right ear. Left ear is positive and bars are 95% CI.

towards the right ear was dominated by flutes held to the right hand side. Bassoon players had brass players on the right side in Orchestra II, which contributed as well. Figure 3 shows the exposure differences in terms of difference in L_{Aeq} over time between left and right ear in different instrument groups.

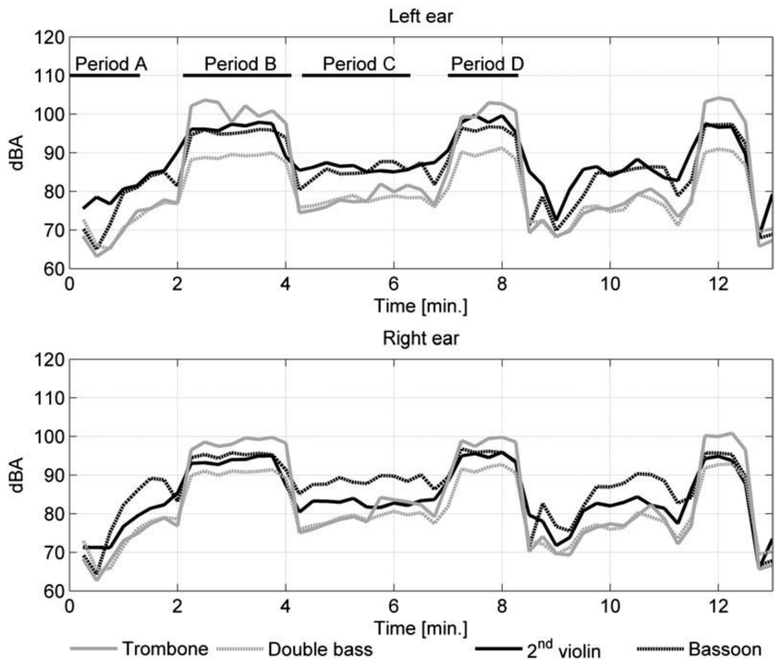

Fig. 4. Variation in L_{Aeq} at the same time for four different instruments playing Gade Ossian overture. Periods A–D illustrate different periods selected for further analysis. Periods A and C are inactive periods for the trombone. Periods B and D are active periods for the trombone.

To investigate the contribution to the total sound exposure from the musician's own instrument compared to other instruments in greater details, a number of measurements were aligned. Figure 4 shows such an alignment of four different instruments playing the concert Gade Ossian Overture in Orchestra I. Periods B and D illustrate two periods where the trombone was active, while Periods A and C illustrate periods where the trombone was inactive. The trombone was exposed ~10 dB more than the double bass during Periods B and D. As shown in Fig. 2, the sound from the trombone is weaker at the level of the double bass due to the distance.

Table 6 shows that musicians except low string players who actively played their own instrument were significantly exposed to higher L_{Aeq} compared to periods where they were passively exposed from the rest of the orchestra. The number of peaks exceeding 115 dBC min^{-1} increased to 3.7 for the active brass players ($P < 0.001$) and to 1.5 more per minute ($P < 0.03$) for timpani players. In contrast, high strings and low strings were exposed to significantly fewer peaks in periods where they were actively playing ($P < 0.01$ and $P < 0.03$, respectively). This can be explained by the fact that when strings were not active, music was solely produced by woodwinds and brass instruments, which generate more peaks, compared to strings. No significant difference in relation to peaks exceeding 115 dBC could be observed in woodwind players.

The weekly working schedules of the two orchestras were similar. Usually, Orchestra I played one concert and Orchestra II played two concerts while 3 days with 4 h of rehearsals were scheduled in both orchestras. The duration of the concerts were typically 2 h with an effective playing time of 96 min in Orchestra I and 87 min in Orchestra II. The effective average playing time during rehearsals was 3 h and 12 min and 3 h and 26 min in Orchestra I and Orchestra II, respectively. The remaining time up to the scheduled 4 h was used on non-music activities including breaks. Table 7 shows the sound exposure equivalent to an 8-h working day within the orchestra but excluding individual practice time based on the effective playing time and the coefficients from the linear mixed effect model in Table 5. The results show that many musicians exceeded 85 dBA at both concerts and rehearsals. The equivalent exposure during rehearsals was of longer duration and therefore exceeded the exposure during concerts.

DISCUSSION

By using a new sound measurement procedure, we have quantified the exposure of individual

Table 6. Linear mixed model of the effect on sound level of active playing on own instrument compared to passive exposure from the surroundings. Coefficient values refer to dBA in the upper part of the table and to number of peaks per minute exceeding 115 dBC in the lower part of the table

Exposure	Coefficient (dBA)	SE	95% Confidence interval (dBA)	
Active/passive musician × instrument group. Reference to passivity. (L_{Aeq})				
High strings	2.7	0.94	0.9	4.6
Low strings	1.3	1.87	−2.4	4.9
Woodwinds	4.7	0.95	2.8	6.6
Brass instruments	7.0	1.01	5.0	9.0
Timpani	2.3	1.37	−0.4	5.0
Active neighbour	3.7	0.61	2.5	4.9
Active/passive musician × instrument group. Reference to passivity. (peaks per min >115 dBC)				
High strings	−1.2	0.49	−2.1	−0.2
Low strings	−2.0	0.95	−3.9	−0.2
Woodwinds	−0.2	0.49	−1.2	0.7
Brass instruments	3.7	0.52	2.7	4.7
Timpani	1.5	0.70	0.1	2.8
Active neighbour	1.2	0.31	0.6	1.8

Table 7. Daily exposure in L_{Aeq8h} of symphony orchestra musicians playing the repertoire of Orchestra I and Orchestra II. The exposure is different in the right and the left ear and there is a small difference between rehearsal and concert

Instrument	Left ear				Right ear			
	Orchestra I		Orchestra II		Orchestra I		Orchestra II	
	Rehearsal	Concert	Rehearsal	Concert	Rehearsal	Concert	Rehearsal	Concert
First violin	86.9	84.9	88.9	86.1	82.1	80.1	84.1	81.3
Second violin	86.2	84.2	88.7	85.9	82.6	80.6	85.0	82.3
Viola	89.3	87.3	91.9	89.2	82.6	80.5	85.2	82.5
Cello	80.1	78.1	83.0	80.3	79.6	77.6	82.4	79.7
Double bass	81.9	79.9	82.5	79.7	82.0	80.0	82.4	79.7
Flute/piccolo	88.0	86.0	90.2	87.5	89.3	87.3	91.6	88.9
Obo	85.4	83.4	85.7	83.0	86.7	87.8	87.0	84.2
Clarinet	87.3	85.3	88.8	86.0	87.3	85.3	88.9	86.1
Bassoon	86.3	84.3	87.6	84.9	87.3	85.3	88.7	85.9
French horn	89.3	87.3	90.7	88.0	89.4	87.4	90.7	88.0
Trumpet	91.0	89.0	91.7	88.9	91.3	88.3	92.0	89.2
Trombone	89.6	87.5	90.3	87.6	88.0	86.0	88.8	86.0
Tuba	n.a	n.a	88.3	85.5	n.a	n.a	87.3	84.6
Timpani	87.1	85.1	88.8	86.0	84.6	82.5	86.1	83.4
Celeste	n.a	n.a	89.8	87.0	n.a	n.a	86.3	83.6

musicians in two symphony orchestras and shown that classical musicians were exposed to loud sounds with L_{Aeq8h} up to 92 dBA, exceeding the allowable 8 h limit of 85 dBA and posing a clear risk of noise-induced hearing loss. The most important risk factor in relation to sound exposure of a classical musician was sound from their own instrument and the highest exposures were found among brass players and the left ear of the high strings. The low strings had the lowest exposure in the orchestra. Thus, exposure is different on the right and the left side depending on the instrument with the most pronounced difference in high string players. The repertoire resulted in significantly different exposures. Knowledge regarding the sound exposure from different repertoires may be an important and easy way to minimize the sound exposure. The musician's sound exposure was dependent on the activity from own instrument and to some degree from neighbouring instruments. Exposures at concerts were found to be slightly more pronounced than during group rehearsals.

To our knowledge, systematic and simultaneous measurement of left and right ear sound exposure has not been carried out for musicians. The placement of the microphones by attachment to the ears was in general well accepted by the musicians while they were more reluctant to wear the noise dosimeter as the microphone placement on the shoulder interfered with the instrument. A previous investigation also reported that musicians were reluctant to wear noise-dose metres because they found them uncomfortable (MacDonald *et al.*, 2008).

It has been speculated that a microphone position too close to the body may result in measurement errors due to the reflection of sounds from the body (O'Brien *et al.*, 2008). We do not believe that this is a major problem since differences between the measurements with the ear mounted microphones and a dosimeter placed according to ISO 9612 were within the generally accepted 2 dB measurement uncertainty (Lee *et al.*, 2005). The measurements in this study reflected the air conduction of sound only, but it may also be speculated if conduction through bone, e.g. the mandibula in violinists may add to this exposure.

This study demonstrates a difference of ~4.6 dB (95% CI 3.9–5.3 dB) between the left and the right ear in the high strings but during periods, the difference could be up to 10 dB (Fig. 3). With two short exploratory measurements in violinists with the head positioned close to erect, a difference of 6–8 dB between the left and the right ear was demonstrated (Royster *et al.*, 1991). Significant side differences were also found for the trombone and flutes. The flutes had higher exposure on the right ear especially during individual practice.

In previous studies, the sound exposure of high strings may have been underestimated. Microphones have been placed at the right side as well as at the left side of the musician. It may have resulted in inaccurate exposure measurements of high string players (O'Brien *et al.*, 2008). Measurements of L_{Aeq} levels at violins have been reported below 90 dB (Obeling and Poulsen 1999; Emmerich *et al.*, 2007; O'Brien *et al.*, 2008). We have measured on both sides of all musicians including high strings. The results from the left ear of the high strings were similar to measurements from the back of the left shoulder, where the exposure of violins has been measured up to 99 dBA (Royster et al., 1991; Nielsen *et al.*, 2010). On the other hand, measurements from the right shoulder of high strings showed L_{Aeq} not higher than 92 dB similar to the findings from the right ear of the high strings in the present study (Camp and Horstman, 1992; Sabesky and Korczynski, 1995; Laitinen *et al.*, 2003; Qian *et al.*, 2011). Thus, accurate assessment of the exposure of the high strings should be carried out on the left side.

The differences between different repertoires have not previously been analysed in a statistical model. In our study, the linear mixed-effects model showed the actual repertoire was a strong factor for the exposure of musicians. The repertoire-specific coefficients varied from −7.3 to 2.3 dB, which equals a difference of 9.6 dB in the Map II model with a mean value of −2.0 dB. At the level of the double bass, this corresponds from 76 to 85.6 dBA. Thus, musician's exposure varied almost 10 dB depending on their actual repertoire. The size of the orchestra seemed to play only a limited role compared to the repertoire. During Carl Nielsen Symphony No.1 in the smaller Orchestra I, the repertoire-specific constant was 2.3 dB compared to the repertoire-specific constant of 0.8 dB for Mahler symphony No. 6 in the larger Orchestra II. Measurements from different classical repertoires previously indicated a possible difference in some studies (Schäcke, 1987; Mikl, 1995; Laitinen *et al.*, 2003; Lee *et al.*, 2005) but not in others (Sabesky and Korczynski, 1995).

Using the statistical model increased, the generalization of the instrument-specific exposures to include other performances. If the mean value of the repertoire-specific coefficients can be regarded as representative for musicians' exposure, a mean exposure for each instruments can be calculated after subtraction of 1.5 dB (Map I model) or 2 dB (Map II model). Map II model has a lower standard deviation of the constant and it is more accurate (Table 5). More measurements from additional repertoires from different situations could possibly increase the accuracy of the model. We included repertoires regarded as loud (Mahler and Carl Nielsen) and more soft (e.g. Sjostakovitj and Schumann) in the model to cover different aspects of classical music. The instrument and the repertoire-specific estimates reflected a likely average estimate of the instrument and repertoire-specific exposure, respectively. Individual differences could give different exposure estimates as the model described a likely average estimate for a certain instrument. Both orchestras played on large stages in concert halls and any contribution of the stage and the room could not be estimated.

The interaction between the instrument and the ear-specific measurement in the model described the exposure difference between the left and right ear. It was obvious that high strings should have an increased exposure on their left side. The exposure of high string players was shown to be 90–93 dBA for the left ear in Orchestra I and 92–96 dBA in Orchestra II based on the linear mixed-effects model.

Musicians could be exposed to potential hazardous sound levels (Jansson and Karlsson, 1983; Woolford, 1984; Royster *et al.*, 1991; Obeling and Poulsen, 1999). Most studies reported exposures $\sim\geq 95$ dBA among brass players especially the trumpet, which was in agreement with the findings in this study (McBride *et al.*, 1992; Obeling and Poulsen, 1999; O'Brien *et al.*, 2008). Timpani and percussion players received more of the sound exposure as impulsive sounds. Peaks exceeding 115 dBC were also frequently found for brass players.

Sound exposure mainly arose from the musician's own instrument. Whenever brass, woodwind, and high strings were active on their own instrument, the exposure was higher compared to a passive exposure from other instruments. Frequent peaks exceeding 115 dBC exposed brass and timpani players from their own instruments. In contrast, both high strings and low strings were exposed to fewer peaks when they were playing compared to inactive periods. This finding was somewhat surprising but it reflected that the highest sound peaks were originating from the brass and percussion sections when the high strings were not playing.

This was also the case if the exposure from neighbouring musicians was taken into account. The exception was the low strings, where no difference in sound exposure could be observed between periods with and without active playing, indicating that the sound exposure in this group was mainly from other musicians in the orchestra. If musicians were positioned even closer to each other, e.g. in an orchestra pit, it is possible that exposure from neighbour positions may play a larger role.

Daily exposures often exceeded L_{Aeq8h} of 85 dB. Most musicians had in addition individual practice, which can be more intense without breaks and it can increase the daily exposure even more. Moreover, higher reflection of sounds may occur in small practice rooms compared to large concert halls, where the group rehearsals occurred. Brass winds and timpani players were frequently exposed to impulse like sounds, which can increase the risk of hearing loss even more. Approximate time for individual practices have previously been reported to 10 h week^{-1} (Laitinen *et al.*, 2003). In our study, musicians reported up to 3–4 rehearsal periods and 1–2 concerts during the week giving a total playing time within the orchestra of 14–20 h week^{-1}. Including 10 h of individual practice, the sum was 24–30 h week^{-1} or 4.8–6 h day^{-1}. This was in agreement with previous observations of 5.5 h day^{-1} (Laitinen *et al.*, 2003). Other orchestras have reported rehearsal periods of 2.5 h and performances of 3 h (Lee *et al.*, 2005; O'Brien *et al.*, 2008). The effective playtime was usually high during performances and a less during group rehearsals. It has been estimated to be 65% during rehearsals in a previous study (Jansson and Karlsson, 1983). In the course of this investigation, it was >80% for both orchestras. Some instrument groups may experience periods with shorter exposure during rehearsals, e.g. brass and percussion players who often do not participate in all rehearsals and repertoires.

Musicians were exposed more than the recommended L_{Aeq8h} of 85 dB during a workday, even if the shorter working periods and the unexposed periods were taken into account. On the other hand, studies evaluating the effects of high sound exposure from music have previously not identified dramatic hearing loss in the group of classical musicians, who on average hear better than or equal to a non-industrial noise-exposed population (Karlsson *et al.*, 1983; Royster *et al.*, 1991; Obeling and Poulsen, 1999). However, signs of noise-induced hearing loss especially in brass players and percussionists have been reported in previous studies (Axelsson and Lindgren, 1981; Westmore and Eversden, 1981; Ostri *et al.*, 1989; Kähäri *et al.*, 2001a). Regarding high strings, some studies reported a tendency to find a more prominent high frequency hearing loss on the left side compared to the right side (Axelsson and Lindgren, 1981; Ostri *et al.*, 1989; Royster *et al.*, 1991; Emmerich *et al.*, 2007). Future studies are still needed to establish a clear association between sound exposure in musicians and hearing loss.

The musicians at risk may develop hearing loss and the use of hearing protectors can be a solution. Intervention should also focus on the actual exposure time. It should include individual practice as this can be an overlooked source of sound exposure. The different repertoires contributed differently to the exposure. With focus on the different repertoires throughout the season, it may be possible with careful planning to reduce the sound exposure of the musicians.

CONCLUSIONS

With a new sound exposure measurement method of both the left and the right ear, we found that the most exposed groups were brass players (86–98 dBA), woodwinds (80–98 dBA), and the left side of the high strings (82–98 dBA). The percussionists as well as the brass players may be exposed to high impulsive sounds as loud sound peaks exceeding 115 dBC often occur in these instrument groups. This may increase the risk of getting noise-induced hearing loss. Since this study shows that musicians are at a risk, especially from exposure by their own instrument, future interventions should focus on protection of the sound from own instrument. This study also confirms that musicians are exposed to an equal extend during individual practice, group rehearsals, and concerts.

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