Sound levels in symphony orchestra musicians

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A symphony orchestra is a complex and powerful sound source, where musicians are both sources and receivers. Instant levels vary a lot from one moment to another, and equivalent levels varies significantly from piece to piece, from one position to another, from one orchestra to another playing the same piece, from one concert hall to another, and so on. Sound level and exposure management has several artistic advantages beyond hearing concerns and should be based on long-term a perspective with a random point sample program for dosimetry over year cycles. As a reference for "normal" exposure, the statistics from more than 1600 dosimeter measurements over 3 years in the Queensland Orchestra is suggested. This paper includes results from etry and other measurements and observations during rehearsals and performances, together with analysis and recommendations for further work in the field. The sound of music in an orchestra is not unwanted and not be handled like noise. Use hearing protection, but not more than needed.

1 Introduction

A symphony orchestra is a complex and powerful sound source, where musicians are both sources and receivers. Instant levels vary a lot from one moment to another, and equivalent levels varies significantly from piece to piece, from one instrument type to another, from one position to another, from one orchestra to another playing the same piece, from one concert hall to another, and so on. Musicians are often concerned about their hearing and the risk of hearing loss, and at least one orchestra has been convicted legally responsible for the hearing loss of a musician. Different kinds of hearing protection are being used, but they come with downsides. Noise is un-wanted sound, while music is not. Still, the sound of music is commonly treated like industrial noise, and its exposure levels compared with limits intended for industry workers. Is this common practice justified? What are the common exposure levels anyway? In general, how do sound levels vary? What are the causes of varying sound levels? Are there other adverse effects from sound levels than health risks? These and other questions are being addressed. Common interpretation of occupational noise regulation limits is at odds with reality in orchestras.

2 Sound levels and level variation from symphonic music

Symphonic music can cause instant A-weighted sound pressure levels (SPL, or L_{pA}) ranging from 20dB to 140dB, depending on time and position in the concert hall or rehearsal room. In various statistical categories, however, the range can be much smaller, and the sound levels can be statistically predictable in terms of probability. This section describes statistical properties in various categories observed from field measurements during symphony orchestra rehearsals and performances.

2.1 Data

2.1.1 O'Brien etry data

A major external source of field measurement data is from the work of O'Brien et.al., reported in 2008, consisting of etry data with equivalent L_{Aeq} and L_{Cpeak} from a total of 1608 sessions, lasting 2.5-3.0 hours, in The Queensland Orchestra, hereafter QSO, over the seasons in the 3-year period 2005-2007 [1]. One half of the sessions are concert performances, mostly in the concert hall of the Queensland Performing Arts Center (QPAC), and the other half partly orchestra pit sessions in the Lyric Theatre and rehearsals in the QPAC Rehearsal Studio. All the raw data has been shared with this author for further and independent analysis.

2.1.2 Own data

Included in the volume of field measured data acquired by this author are etry data in two Norwegian symphony orchestras, in this paper referred to as Orchestra A and Orchestra B, or just A and B, together with sound level data in selected fixed stage and auditorium positions. These measurements include level-time data in 1 second resolution from eters (Casella dBadge) and sound level meters (Norsonic N-140) in metrics $L_{pA,eq}$ and $L_{pC,peak}$ from each session, where some sessions are rehearsals, but most of them are concert performances. Moreover, own data includes 30 hours of binaural data recorded in concert listener positions during concerts with various orchestras in various halls in Europe and USA, i.e. in the Binaural Project[2].

2.1.3 Other

From the Binaural Project, there is more than 1 million sound pressure levels measured in 100ms windows from symphonic music in listening positions. A total of 114 measurements covering 106 h were recorded in musicians in two symphony orchestras, analysed and reported by Schmidt et.al.[3].

Wenmaekers has developed a prediction model for sound levels in musicians in symphony orchestras, published in a series of papers and with data collected in a book [4] (2017), mentioned here for any readers who are interested in comparing predicted and measured results in comparable metrics, in particular the variation in exposure levels over various positions in a symphony orchestra.

2.2 Level distributions and statistical sub-populations

Data can be viewed as a global population of all instant sound pressure levels or as sub-populations based on relevant categories of data. Thus, data from all instants in one instrument or orchestra position could form a sub-population of data. Another population could be the population of sessions in each instrument, based on its $L_{pA,eq}$, $L_{pC,peak}$ or other statistics. Yet another population could be the population of instruments, e.g. their $L_{pA,eq}$ values in one session or any number of sessions. Each population and sub-population can be relevantly described by common statistics like its average, standard deviation, percentiles, skewness of gaussian distribution, and so on, and graphically by e.g. its histogram.

Typically, the global population of all data, with instant levels at all times and all positions, has a gaussian or near-gaussian distribution with the bell-shape slightly skewed to the right in a histogram. In listening positions,

2.2.1 Metrics

Measured sound level metrics $L_{pA.eq}$, $L_{pC.peak}$ from sessions (rehearsal or performance), and instant levels from level-time data in terms of LpA in 1 second resolution, and broadband (0.4-2.5kHz) levels in 1 second, L_{1s} , and 100 milliseconds, L_{100ms}, all in dB, form the database for the work presented in this paper.

2.2.2 Global statistics - listening levels in live symphonic music

Table 1 presents statistics from all instant broadband levels with 100ms resolution measured in listening positions during symphonic music performance, data collected in the Binaural project. N is the count of instants/events, Leq is the equivalent level (level of average energy), L88%, L75%, L50% and L25% are percentile levels, m the average level, s the standard deviation and skew the skewness of the bell shape. All levels are in dB. Figure 1 is the histogram of the global population of broadband listening levels, where the skewness of the bell shaped gaussian distribution can be observed by its somewhat longer tail to the left and shorter to the right. The most frequently occurring level, i.e. the *mode*, is observed to be somewhere in the 63-69dB range. Note that the equivalent level equals the 88-percentile, demonstrating that equivalent level is dimensioned by the louder members of the population.

Table 1 Statistics of listening levels during live symphonic music, see text

N	L_{eq}	L88%	L75%	L50%	L25%	m	s	skew
1011189	80	80	73	64	54	63	15	-0.5

For the purpose of this paper, the skewness of the distribution will be evaluated by the following rules of thumb: 0-0.5 is close to symmetry, 0.5-1.0 is moderately skewed, while >1.0 is highly skewed, and of course the sign of the value determines whether the skewness is positive or negative.

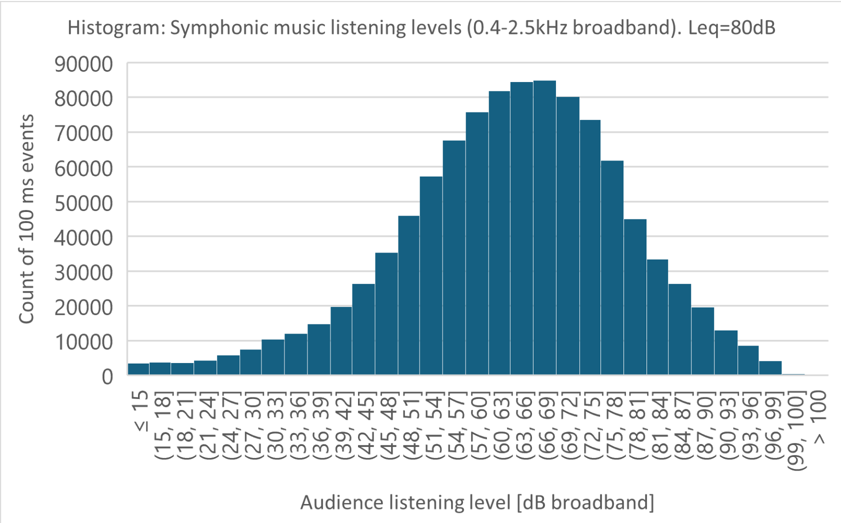

Figure 1 Histogram of 100ms events of broadband sound pressure levels from symphonic music in listening positions

2.2.3 Concerts as sub-populations

If the global data above is grouped into sub-populations of data from the individual concerts, there would an individual set of set of statistics for each concert, e.g. $m_{concert}$ and $s_{concert}$. From the data, $m_{concert}$ would normally be somewhere in the 56-70dB range and $s_{concert}$ in the 10-14dB range, thus a typical concert would have a high likelihood of levels 63±12 dB, i.e. a normal range of 51-75dB. From this we note that the spread of the global data is partly made up by the level variation within in each concert, partly by the variation of average level from one concert to another.

2.2.4 Levels in performers versus levels in listeners

At performers positions, the level distribution profile is observed to be quite equal to that of the listening positions, only with averages 5-7dB higher on stage due to attenuation from stage to the listening positions in the audience area. Similarity of distribution profiles is to be expected since high quality sound transmission is essential in concert halls, and both are determined by the music.

2.2.5 L_{Aeq}, L_{Amax}, and L_{Cpeak} in musicians

In occupational noise & health concerns, the daily or weekly dose of sound exposure is often considered, in addition to the loudest sound during the exposure period.

A daily (permissible) dose is commonly defined as equivalent to the sound exposure from an A-weighted sound pressure level of 85 dB with a duration of 8 hours, denoted $L_{pA,eq,8h} = 85\ dB$. For this reason, $L_{pA,eq}$ is a relevant metric. Moreover, it has been and still is a common, practically hard-wired, metric in measuring equipment, which over the years has led to an accumulating volume of measurement data, reference values and limits based on L_{pA}. The equivalent level is obtained by integrating the squared sound pressure and divide by the integration time.

In order to manage the exposure from very loud events, two metrics have been used, i.e. $L_{pFA.max}$ and $L_{pC,peak}$. The former is the highest A-weighted level measured with the time constant “Fast”, i.e. measured in a 125 ms window, while the latter is the level from the highest occurring squared sound pressure, regardless of duration, in the period being measured. Common limits have been $L_{pFA.max} = 110dB$ and $L_{pC,peak}$ = 130dB or 140dB.

In this paper, the notation L_A will be used for L_{pA}, and $L_{C,peak}$ or just Cpeak for $L_{pC,peak}$.

Based on data from the Queensland project (O’Brien), statistics are given in Table 2. In Timpani and Percussion, equivalent levels may be measurements of sound from others in their position at the back of the orchestra than sound from their own instruments. On the other hand, Cpeak-levels in Timpani and Percussion are most likely determined solely by sound from their own instruments, while Cpeak-levels in other instruments may well be influenced by sound from

Timpani and Percussion. The total number of measured sessions is *N=1619*, each session lasting on average two and a half hours, statistically 154 ± 41 minutes.

Table 2 Statistics from etry in the Queensland Orchestra 2004-2007 (data from O'Brien), averages *(m)* and standard deviations *(s)*, number of sessions measured *N*

	Bass	Bassoon	Cello	Clarinet	Flute	Horn	Oboe	Trombone	Trumpet	Tuba	Viola	Violin1	Violin2	Timpani	Percussion	avr(15)
N	79	135	46	155	151	273	90	157	212	24	79	26	62	63	67	108
LAeq (m)	84,5	87,6	84,6	87,9	87,9	89,2	87,0	88,6	89,4	87,1	85,3	84,2	84,7	87,7	88,8	87,0
LAeq (s)	3,0	2,7	2,7	2,7	2,7	2,7	2,4	3,0	3,1	4,2	3,6	3,0	2,7	3,9	3,1	3,0
LCpeak (m)	123	123	122	123	121	123	121	128	126	127	121	120	120	133	136	124
LCpeak (s)	5,4	5,2	5,1	4,4	4,1	3,7	3,8	4,8	4,6	5,0	5,4	5,7	4,6	4,2	6,2	4,8

In practice, each session would include various compositions with various instrumentation and sound power, and several would consist of a typical all-night concert program. The standard deviation of separate compositions would probably be bigger than the standard deviation of sessions like in this table.

For the average instrument, $L_{A.eq}$ would normally be within 84-90 dB, and on average 87 dB. The loudest positions are those of Horn and Trumpet, normally within 87-92 dB.

As to the loudest instant of a session, $L_{C.peak}$ for the average instrument would normally be within 119-129 dB, on average 124 dB. The positions with the loudest instants are those of Timpani and Percussion, with peaks normally within 129-137 dB and 120-142 dB, respectively. The loudest peaks recorded are a few occasions of 147dB in Percussion.

2.2.6 Dose

Further to section 2.2.5, the dose D [%] can be calculated from sound exposure of any level and duration, with D=100% equal to the common daily permissible dose (DPD), equivalent to 85dB over 8 hours, from the following formula:

$$D\ [\%] = t/480 \cdot 10^{x/10}\ , \qquad (1)$$

where $x=L_{A.eq}(t)-85dB$ measured over work hours a given day, and t is the total duration of the measurement(s), in minutes.

In the Queensland data, statistics of the 1619 measurements reveals that the normal dose is within 17%-137%, with the average dose *D= 77%.*

1 out of 4 sessions exceeded the daily dose.

DPD originates from industry noise regulations, suitable for work environment with little day to day variation in sound exposure, assuming 8 hours a day, 5 days a week. In contrast, occupational sound exposure in a symphony orchestra is very different from that of an industry or industry-like workplace. Sound levels vary from second to second, minute to minute, hour to hour, day to day, and even from one week to another. In order to arrive at empirically based knowledge about permissible doses for orchestra musicians, on would need to know the weekly and yearly doses too. Moreover, literature suggest that hearing loss (PTS, permanent threshold shift) from industry noise accumulates over years [5], implying that long-term exposure time matters, and that even a 10-year dose should be calculated when investigating any adverse effects from sound exposure in musicians.

The weekly dose can be calculated from:

$$D_{week}\ [\%] = t/3360 \cdot 10^{x/10}\ , \qquad (2)$$

where $x=L_{A.eq}(t)-85dB$ measured over work hours a given week, and t is total measurement duration, in minutes.

The principle from (1) and (2) can be extended to any long-term windows as fit. However, measurements and calculations of long-term doses can be impractical, and methods based on point samples and statistics should be consider in order to efficiently acquire a large amount of data with high statistical quality. Given the purpose of these measurement, and because time and resources are limited, the number of measurements would be prioritised over the accuracy of each single measurement.

2.2.7 Queensland statistics as reference for measurements in other orchestras

When seeking a statistical reference for "normal" sound levels in orchestras, it is important to include all relevant types of activity. Since the sound exposure inherent in the activities naturally varies from week to week, but less so from year to year, we would need data from at least one year.

The Queensland data (O'Brien) is acquired over 3 years and can be considered representative for the expected sound exposure in a symphony orchestra. This author has suggested the statistics from these data as an objective reference indication of whether measured levels are normal, or higher or lower than normal, i.e. inside the interval {m-s, m+s} for a given instrument or position. In a number of sound level mapping projects commissioned by symphony orchestras since

2013, this author has found it relevant to compare results with the statistics from the Queensland data, as presented in the next section.

3 etry and sound level mapping commissioned by symphony orchestras

3.1 Random or biased selection?

Some symphony orchestras want, for various reasons, to have knowledge about the sound exposure levels in their musicians, some because of issues or complaints from musicians, others just for the knowledge or because they want to be reassured that they are within normal.

It is important to keep in mind that the reasons for commissioning measurements will inevitably be a filter. If the orchestra for some reason prioritise to measure the presumably loud concert programs, their collected data would obviously not be a random selection, but a collection of sound levels above normal. If they instead seek to manage their seasonal or yearly program with the aim to have levels within normal, a more random selection approach should be chosen.

3.2 Project cases

As a consultant, this author has carried out etry and sound level measurements in several sound mapping projects since 2013, in two orchestras, commissioned by the orchestra administrations, in three concert halls.

- 2013: Orchestra A, Hall 1, Schönberg; Pelleas und Melisande; rehearsals and concert
- 2017: Orchestra A, Hall 1, Williams; Star Wars; rehearsals and 2 concerts
- 2019: Orchestra B, Hall 2 and Hall 3; Sibelius, Shostakovich, Brahms; rehearsals and 2 concerts
- 2020: Orchestra A, Hall 1, Debussy's Images, Ravel's Bolero; rehearsals and 1 concert
- 2022: Orchestra A, Hall 1, Mahler III; rehearsals and 2 concerts
- 2023: Orchestra A, Hall 1, Brahms, Stravinsky, Shostakovich; 2 days, trials with varying acoustics

3.3 Results

In Figure 2, resulting equivalent levels are presented for eters in 14 instruments/positions from the sound level mapping projects described above, together with the results by Schmidt and the 3-year average from Queensland (QSO). The vertical bars represent the "normal" over 3 years, based on the Queensland data. A similar presentation is given for Cpeak-data in Figure 3. Compared to the 4250 total hours of etry in Queensland, the results reported here add up to 554 hours of etry.

3.4 Comments

Equivalent levels in first violins are largely within the normal for their instrument and position in all the cases. The same goes for Timpani, but only two cases are included. All other instruments have levels significantly above normal in one or more cases. The music in Star Wars is very loud for obvious reasons (wars are inherently noisy) due to the extended use of brass in its orchestration. Mahler, too, with a big horn section and strong brass parts which tend to increase levels not only in the brass sections, but also in the woodwinds in front of them, not least because of directivity in trumpets and trombones. The latter is also the reason for the exceptionally high levels in the Double Bass during Star Wars.

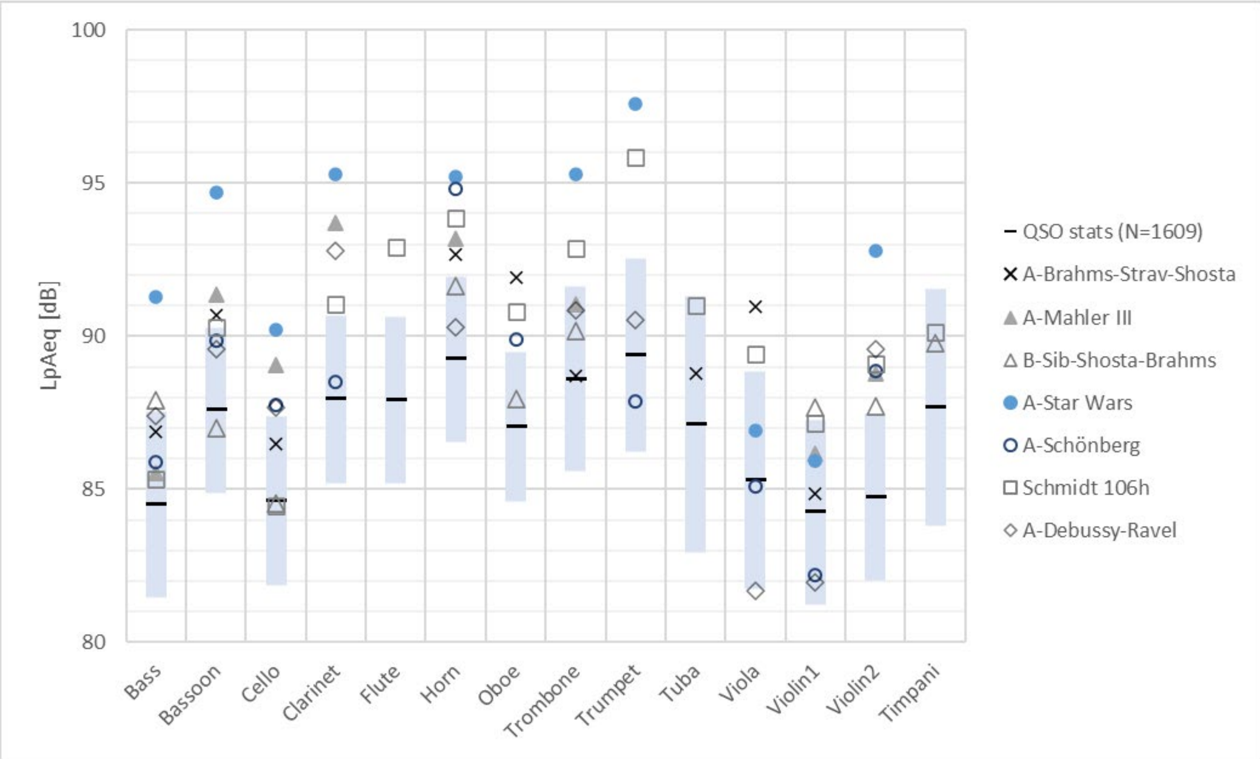

Figure 2 (above) L_{Aeq} from various measurements in 14 instrument groups in symphony orchestras; shaded bars indicate normal levels. See text for details and comments.

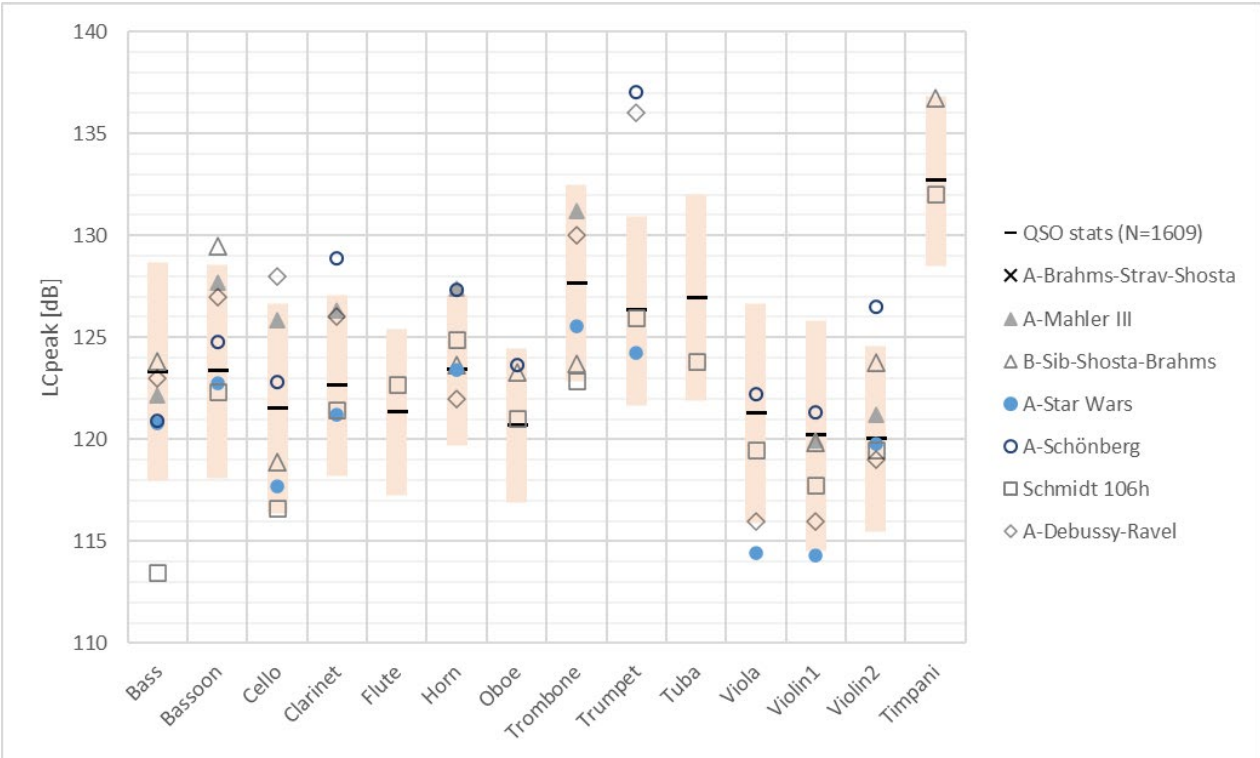

Figure 3 (above) $L_{C,peak}$ from various measurements in 14 instrument groups in symphony orchestras; shaded bars indicate normal levels. See text for details and comments.

In contrast to the equivalent levels in Figure 2, Figure 3 reveals that peak levels are largely within normal values, with the exception of Trumpet, which is approximately 1 sigma (1 standard deviation), 5-6 dB, above normal values during Schönberg and Ravel. Basson, Clarinet, Cello and 2nd violin exceed normal values by less than a third of sigma. Interestingly, while the Star Wars concerts exceed the normal range of equivalent levels by ca. 1 sigma in 8 out of 14 instruments, its peaks are within normal, and even slightly below normal in Viola.

One cannot conclude from the results in Figure 2 and Figure 3 whether or not exposure levels in Orchestra 1 and Orchestra 2 are normal in the long run. Since the measurements are commissioned, they are potentially biased. Actually, they are motivated by the orchestra management suspecting the measured projects to be rather loud.

Sound level and exposure management should be based on a long-term random point sample program for dosimetry over year cycles.

3.5 Other observations

3.5.1 Balance between reverberant sound and dry (non-reverberant) sound

With synchronized microphones in suitable positions in the room, it is possible to measure the reverberant sound in the concert hall, with the same resolution (1 second window) as that in the eters. With this information, the dry component of the orchestra, i.e. the sum of non-reverberant sound from own instrument and others', can be calculated at every eter position by subtracting the energy of the reverberant sound from the energy measured at the eter, for every 1 second window. In this manner a total of four time-varying levels with 1 second resolution can be acquired from each individual eter:

- *L_{pA} (t)* *[dB]* *sound pressure level at dosimeter*
- *R (t)* *[dB]* *reverberant energy level on stage*
- *D (t)* *[dB]* *dry, i.e. non-reverberant, energy level at dosimeter*
- *D-R (t)* *[dB]* *dry-reverberant balance*

Here, *L_{pA} (t)* is the time-varying eter signal, *R (t)* the time-varying reverberant sound level on stage, *D (t)* is the time-varying dry component, and *D-R (t)* the time-varying Dry-Reverb balance. The dry component can be calculated with the following formula:

$$D(t) = 10 \cdot log\left\{10^{\frac{L_{pA}(t)}{10}} - 10^{\frac{R(t)}{10}}\right\} \qquad [dB] \qquad (3)$$

3.5.2 Possible adaptation to different acoustics the next day

In 2019, Orchestra B rehearsed Wednesday and Thursday, and performed the program in a concert Thursday evening in Hall 2. The next day, Friday, they moved to Hall 3 situated in another city where they had a brief rehearsal and performed the exact same program in the evening as the evening before. Interestingly, the sound levels in dosimeters were 1-2 dB softer, but in the stalls, levels were equal to those the evening before. The difference is not big, but given the repeatability of this orchestra, it is significant.

A possible explanation is that they know both halls very well because they play there frequently. They know that Hall 3 has a higher room gain (G) and know that they can play more relaxed and still achieve the proper levels in the audience.

4 Management of sound level, exposure, and hearing protection

"The more hearing protection they use, the louder they play." Managing director of Orchestra 1.

And - the louder they play, the uglier the sound, one might add.

Sound level management has two quite different advantages. One is obviously about the risk of hearing damage in the musicians, the other on is the artistic one: The sound quality.

4.1 Implications for sound quality

Whenever a musician plays louder or quieter, the sound level changes of course, but more importantly, the sound quality changes. A higher A-weighted sound power output from an acoustic instrument always comes with more brilliance because the power increase is inherently stronger in higher frequencies than in lower frequencies, and vice versa. Louder means more brilliant sound and quieter means more warm sound. Too loud means harsh and too quiet means dull. So – when does the individual musician play too loud or too quiet? The conductor has an opinion of course, an implication from the conductor's interpretation of the actual piece, including the composer's intention.

4.2 Composers' sonic palette

In this section, this author chooses to highlight the composer's intention and its imperative for sound level management.

A composer has an idea about how the piece should sound among the listeners in the audience. In making this idea become real, there are some basic tools, and they are inevitably linked to how the instruments are being played. Various instruments have different sound powers at one and the same dynamic notation, e.g. *mf* when playing mezzo forte, but they also have different frequency profile (spectrum) and therefore different timbre and sonic character. At forte and fortissimo the differences in character will be even bigger. The various power and sound character of various instruments is for a composer like a palette of colours for the painting artist. Instruments with less power, like violin and viola, can be grouped to become loud enough for their voice to be heard. If the composer wants a melody to be voiced with the character of an obo solo, an instrument among the less powerful, it can still be heard with the proper orchestration, e.g. with strings playing softly at piano with a *p* in their scores.

4.3 An orchestra's investment in sound quality

When managing balance between the various voices, it is crucial to be conscious about the intended sonic character. An instrument group can deliver the same loudness in principally two different ways – either a bigger group playing softer or a smaller group playing louder. The former would sound warmer, and the latter more brilliant. For this reason, an orchestra will employ 60 musicians for the full string group because the composition demands it, instead of having just 30 playing 3dB louder. When investing such a big amount of resources to make it sound right, i.e. according to the composer's intention and orchestration, they should naturally be careful not to waist it by having the orchestra playing loud and harsh. However, long-term increased levels because of forced playing easily happens without noticing.

4.4 Factors affecting level and quality

Quite a few factors can lead to excessive powerful playing style, or not so. Some of them are long-term effects, and some are self-reinforcing.

- Conductors' interpretation, personal taste and preference, and methods and tools for evaluating the orchestral sound
- Principle Conductors' philosophy, working methods, consciousness and emphasis on long-term development of the orchestral sound
- Any occurring misbalance is often easier to correct by demanding "more" from some, than "less" from all others
- Early decay time on stage, because proper feedback from the hall, effectively measured by *EDT*, would intuitively reassure the individual musician that music is being conveyed to the listener, and directly stimulate a more relaxed playing style
- Strength of reverberant sound G_r, including the spectral balance (dull-warm-neutral-brilliant-harsh)
    - Similar to *EDT* above, but effective even during sustained notes, chords and other stationary parts
    - Because it offers feedback to the individual musician in terms of "too strong, too soft"
    - Because too high brilliance comes with too dense high-frequency sound which makes hearing own and other's instruments more difficult
- Excessive use of hearing protection (ear plugs), because the intuitive sense of "too much" is suspended

4.5 Noise & Health

This author has repeatedly voiced that the sonic environment in which orchestra musicians work is not noise, and that sound exposure cannot be adequately managed similar to noise in e.g. industry. To the knowledge of this author, there is no scientific substantiation for the equality of sound exposure in the industry and in an orchestra, even if measured daily doses are equal. Even in one of the largest health studies ever performed, HUNT [6], including 250.000 persons since 1987Age, apart from ear infection is the dominant factor in hearing loss, and the only profession with raised risk is hunters because of the gunshots. Musicians, let alone orchestra musicians, are too few to form a statistically valid sub-population.

In a London court, an orchestra was convicted responsible for the hearing damage to one of their musicians, due to close-range exposure from brass instrument(s) in an orchestra pit. This should be a reminder to avoid obvious risk from powerful directive instruments at short distance from an instrument to a colleague's ears, like trumpet and trombone.

An active Noise & Health policy administrated by the orchestra organization is mandatory, but in the end, individually adapted hearing protection and personal, cautious practice is crucial.

- Never point a trumpet or trombone toward a colleague's head at short distance
- Soloist singers should face the auditorium when singing, even in rehearsals
- The use of in-ear hearing protection should only be used to reduce exposure to the recommended limit, 85 dB
    - For most musicians 1- 5 dB would be sufficient in most cases
    - Since the smallest available documented attenuation is 9dB, musicians should learn to roll their own cotton plugs and have the achieved threshold shift tested by audiographer
- A screen can protect against strong exposure from powerful instruments behind in loud parts and improve the overall listening balance in favour of instruments in front, typically the strings. However, increased sound levels from own instruments have been measured and should be considered in the sound exposure perspective
    - Screen type 1: Typically, a plexiglass screen, reflective on both sides, like Falko S300, Figure 4
    - Screen type 2: A U-shaped screen formed in a headrest-like position in which the musician can lean backwards into on demand, w/wo a soft lining, when sound exposure from behind is strong, Figure 4
- If needed, use hearing protection during solitary practice

Figure 4 Screens, Falko S300 (left), Hearwig and Goodear (right)

5 Further work

In future work, this author aims to acquire more data on variation from piece to piece and the population of concerts and projects through a year cycle. This could provide helpful information for the advice of orchestra managements in their pursuit to plan their program in order to achieve a healthy sound exposure load in their musicians.

Moreover, the time-varying Dry-Reverb balance will be investigated further, and so will the possible effect of *EDT* and G_r on self-reinforcing sound levels.

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