SOUND LEVELS AT MUSICIANS' EARS FROM CLASSICAL INSTRUMENTS DURING SOLITARY PRACTICE

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ABSTRACT

Sound power levels, dry SPL components, and reverberant SPL components have been deduced in two different ways from data reported by O'Brien (2013), after a measurement series on music instruments during solitary practice: 1) from a 3D-model, simulating O'Brien's measurement setup, 2) from a model based on classical theory.
The results would be relevant to noise & health issues as well as for ensemble play issues like hearing balance between self and others, mutual hearing, masking from others, masking from room, the driving elements in the mechanisms of escalating sound power, and a room's influence on long-term development of orchestra playing style, etc.
A list of dry component SPL values at *forte* for 17 musical instruments is suggested, together with a calculation scheme for total SPL at musicians' ears for the sound power levels in ISO 23591 Annex A, and examples from a typical practice room complying with the standard.

Keywords: *music instruments, music practice, noise & health, sound exposure, dry-reverberant-balance.*

1. INTRODUCTION

The sound from a musical instrument during solitary practice at the musician's ears can be separated into two mutually excluding components, namely the dry component and the reverberant component. In this paper, the dry component is understood as the part of the sound from the instrument that arrives at the ears without being reflected from the room.
Note that the dry component differs from the theoretical direct sound from a source to a receiver in free-field, because the dry component is received at the ears on the musician's sound-reflecting head and includes diffracted sound and reflections off the musician's body.
The separation into two dichotomic components is also consistent with the division between the musician's domain and the acoustician's domain, making it easier to assess the influence of room acoustics and the potential for making any improvements.
While the recent standard for music rehearsal rooms and spaces (ISO 23591) contains information about sound power levels from music instruments at forte, together with a method for estimating the sound pressure levels (SPLs) of reverberant sound from a range of classical instruments, it does not provide information about the dry portion of sound from the same instruments. Thus, the standard lacks the necessary information for estimating the total SPL at the musicians' ears during solitary practice, ensemble rehearsals or performance.
By providing the lacking information about the dry part and the corresponding sound power from an instrument, one would be able to calculate 1) the total sound from the instrument at the musician's ears, 2) the level balance between the dry and reverberant component.
This paper presents the information for a range of common instrument types when played during solitary practice.
This extra information would be relevant to noise & health issues as well as for ensemble play issues like self-hearing, mutual hearing, masking from others, masking from room, and for understanding the driving elements in the mechanisms of escalating sound power, and a room's

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influence on long-term development of orchestra playing style.
For brevity, the dry component from a musician's own instrument at the ears of the musician is termed the Dry Self component. In orchestra models, Dry Self is one of the principal sound components together with Other and Room.

2. PREVIOUS WORK

Relevant previous work within the scope of this paper includes the works of O'Brien[1], Skålevik [2][3][5], and Wenmaekers[4]. Compared to [5], the present paper includes more information, plus corrected data for Bassoon.

3. METHOD

In current work, this author has aimed to extract the Dry Self component by two different methods, 1) simulations with Odeon 17 in a 3D model, and 2) with a classical theory model. The latter will be described later.
In the 3D-model this author simulated the measurements on professional musicians employed in Queensland Symphony Orchestra during solitary practice performed and reported by O'Brien (2013) [1]. Through sufficient iterations while varying the power and position of the source, aiming for least possible difference between simulated results and O'Brien's results, sound power levels and dry SPL components could be extracted from the model. Simulations were performed in the software Odeon 17, using its built-in directivity functions for each musical instrument as a source. When best-fit condition was achieved, dry SPL at the musician's ears was measured in a "Black" version of the model, eliminating all reflections from the room by setting room surface absorption to α=1. Once the dry component was established, the room component could be calculated by subtracting the dry component from the total sound measured by O'Brien.

4. THE 3D-MODEL IN THE CURRENT WORK

The one and same room, regularly used for solitary practice, was used throughout all of O'Briens measurements. Dimensions were H·W·L = 2.8m ·4.0m ·4.8m = 54 m^3.
A 3D-model was built according to O'Brien's description of the measurements reported in 2013, including microphone positions, musicians' position and orientation, and surface treatment of the room. These factors were invariant throughout the whole measurement program. See illustrations in Figure 1, Figure 2, Figure 3 and Figure 4.
The measurements were performed during a typical solitary practice program prescribed by O'Brien, with 19 instrument types, 1-3 instrumentalists on each instrument, involving a total of 35 musicians and instruments.

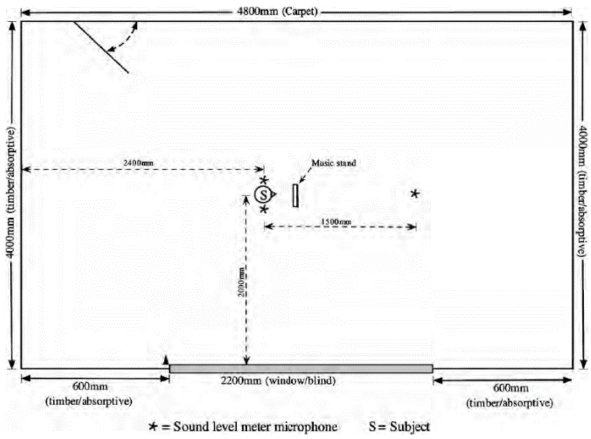

Figure 1 Room plan from O'Brien's paper

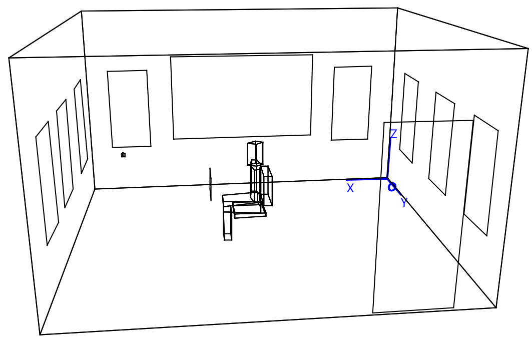

Figure 2 The wire mesh model in current work

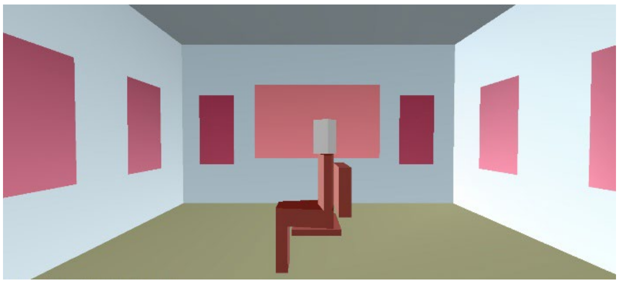

Figure 3 Interior view in the Odeon model built to emulate O'Brien's measurements.

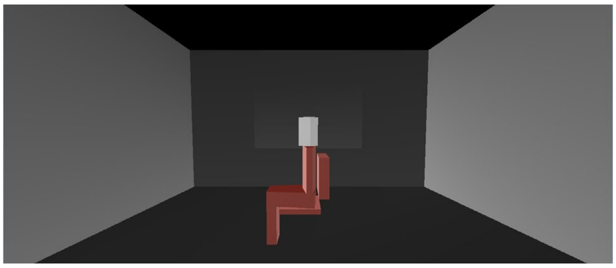

Figure 4 Interior view in the "Black" version of the room model, where all room surfaces are fully absorbing (α=1), to extract the dry component of the sound from a music instrument.

5. INPUT DATA

According to the method described above, measurement data reported by O'Brien was used as input in the process, in the sense that iterations aimed for simulation results best fit to the measurement results in Table 1.

Table 1. Input: Measured SPL values at left ear, right ear and at 1.5 m distance in front of the musician, as reported by O'Brien.

Instrument type (no. of musicians)	*Left ear* $L_{pAeq,23min}$ *[dB]*	*Right ear* $L_{pAeq,23min}$ *[dB]*	*1.5m* $L_{pAeq,23min}$ *[dB]*
Trombone (2)	96	96	94
Eb clarinet (1)	96	94	88
Bb clarinet (2)	92	92	86
Bass clarinet (1)	90	90	86
Trumpet (3)	96	95	93
Horn (3)	92	95	90
Flute (2)	93	95	87
Tuba (1)	95	92	88
Violin (2)	89	86	77
Viola (2)	88	83	74
Bassoon (2)	87	89	83
Oboe (3)	85	85	82
Cello (3)	80	80	75
Double bass (2)	75	75	74

6. RESULTS FROM 3D-MODEL SIMULATIONS

In the iteration process described above the power and position of each source, i.e. musical instrument, was varied until the difference between measured data in Table 1 and corresponding simulated data arrived at a minimum, i.e. the model condition judged to be best fit to O'Brien's measurements. In this best-fit condition the power level of the model's source was read and written into the leftmost output column, *Lw* in Table 2.

Further, for each instrument, the dry sound components at the left and right ears were simulated with the best-fit source power and position with all room surfaces "black", i.e. fully absorbing (α=1), see Figure 4, and written into the output columns *Lp,L* and *Lp,R* , respectively, in Table 2.

Table 2. Output: Sound power levels (*Lw*) and dry sound components at left and right ears, *Lp,L* and *Lp,R* , respectively, taken from the best-fit source power and positions of each instrument type in the model, see text.

Instrument type (no. of musicians)	*Lw [dB]*	*Dry,L [dB]*	*Dry,R [dB]*
Trombone (2)	101	95	95
Eb clarinet (1)	96	96	93
Bb clarinet (2)	94	91	91
Bass clarinet (1)	94	89	89
Trumpet (3)	101	95	93
Horn (3)	100	90	94
Flute (2)	95	92	95
Tuba (1)	98	94	90
Violin (2)	86	89	86
Viola (2)	82	88	83
Bassoon (2)	91	87	88
Oboe (3)	89	84	84
Cello (3)	83	79	79
Double bass (2)	81	73	73

7. DISCUSSION OF RESULTS FROM 3D-MODEL

7.1 Possible error sources

In general, an iteration process aiming for a minimum difference between simulations and a given data set, involves the risk of arriving at a local minimum. This means that there could exist combinations of source power and positions that would yield even smaller differences between simulations and measurements than those found in current work.

7.2 Sensitivity to source-receiver distance and directivity

The simulated SPLs at the musicians' ears are very sensitive to instrument directivities, to orientations in the model, and to small changes in distance between point source, i.e. the centroid of the musical instrument, and the receiver, i.e. microphones 7cm to the sides of the head. Moreover, Odeon is not a wave-based simulation program, so complex diffraction around the head is not well accounted for with violin, viola and other instruments that would leave one of the ears in the sound shadow.
The SPLs at 1.5m are less sensitive to the differences in instrument position but could be very sensitive to directivity from wind instruments.

8. RESULTS FROM CLASSICAL THEORY

Unlike the aforementioned sensitivities, the reverberant sound received by the 3 microphones is mainly dependent on sound power, thus less sensitive to directivities, and very little sensitive to the differences in source position. For this reason, the dry components calculated with classical theory, with the relationship $Lp = Lw\text{-}31\text{+}G$ *(dB)*[1]. *Lw* is calculated from O'Brien's center microphone measurements at 1.5m, assuming directivity index +3dB in the axis of trombone, trumpet, horn and tuba, while other instruments are assumed omni-directional. *Dry,L* and *Dry,R* were calculated by subtracting reverberant sound energy from measured values at ears in Table 1. Results are given in Table 3.
Comparison between values in Table 2 and values in Table 3 reveals that dry components at the ears of the musicians are on average 0.7dB stronger in Odeon simulations than from classical theory, with RMS difference 0.9dB, while L_w values are 1.2dB higher, with RMS difference 0.9dB. These differences are due to reverberant sound predicted by classical theory being stronger than that simulated in Odeon. The practically relevant relationship $L_{dry} - L_w$ is 0.6dB lower from classical theory than from Odeon. It is not concluded which one of the data sets is more reliable. However, differences in the order of 0.6 to 1.2dB are of relatively little significance in the scope of this paper, since the error from ignoring the dry sound component is up to 16dB, as will be explained below. Moreover, while Odeon simulations have been restricted to the 15 instruments having directivity data coming with the software, classical theory method can be applied to all 19 instrument types in O'Brien's report.

Table 3. Results from classical theory, comparable with those from Odeon simulations in Table 2.

Instrument type (no. of musicians)	*Lw [dB]*	*Dry,L [dB]*	*Dry,R [dB]*
Trombone (2)	100	93	93
Eb clarinet (1)	95	95	93
Bb clarinet (2)	93	91	91
Bass clarinet (1)	93	88	88
Trumpet (3)	99	94	92
Horn (3)	97	87	93
Flute (2)	94	92	94
Tuba (1)	95	94	90
Violin (2)	84	89	85
Viola (2)	81	88	82
Bassoon (2)	90	85	88
Oboe (3)	89	82	82
Cello (3)	82	78	78
Double bass (2)	81	69	69

9. IMPORTANCE OF INCLUDING THE DRY COMPONENT

Keep in mind that from the data in ISO 23591 Annex A, only room levels, i.e. reverberant sound pressure levels, can be calculated. To demonstrate the importance of the results from current work, the calculated difference between SPLs at musicians' ears and SPLs of the reverberant sound field is shown in Figure 5. The SPLs at musicians' ears will be between 1dB and 14dB stronger than SPLs from reverberant sound alone. These

[1] Reverberant energy strength at 1.5m was assumed *Gr=23 dB* according to Barron's Revised Theory (BRT) and ISO 23591 Annex A, Volume *54m3* and *T=0.42s*. Difference in *Gr* between the three microphone positions in measurements in Table 1, theoretically *0.0-0.6dB*, are considered insignificant, given the accuracy in this scope.

differences depend on instrument type and prediction model. Without information about the dry component, the total SPL at musicians' ears will be underestimated by on average 6dB with classical theory and 8dB with Odeon simulations.

10. LEVEL BALANCE BETWEEN INSTRUMENT AND ROOM

Another relevance of Figure 5 is that it illustrates to what degree the sound from the instrument dominates over the sound reflected from the room. The lower the bars, the more will the room acoustics play a part in the sound that the musician perceives, and vice versa. At the double bass player's ear the sound would be only 2-4dB louder than the reflected sound alone, while at the viola player's ear, the viola sounds 12-14dB louder than the reflected sound alone. A different illustration of hearing balance between instrument and room is given in Figure 6, while implications to sound exposure and Noise & Health are discussed over Figure 7 in the section below.

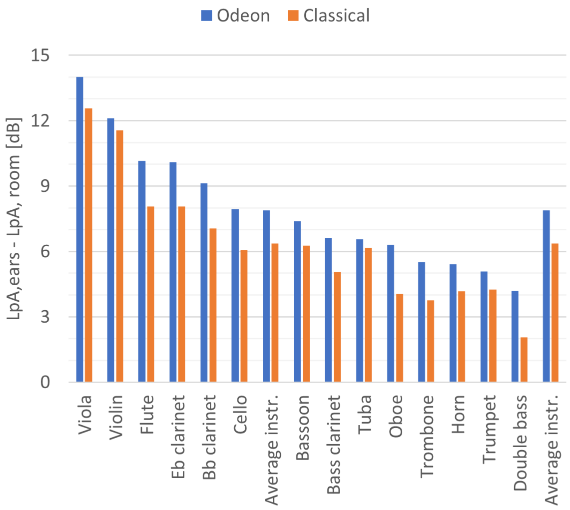

Figure 5. Difference between SPL at the musician's ears and SPL from the room (i.e. the reverberant sound field), from Odeon model and from Classical theory.

Figure 6 shows the two energy components Instrument (dry component) and Room (reverberant energy) in % of total sound energy at musicians' ears for the various instruments. The average musician receives 79% from the instrument and 21% from the room. The big differences in the instrument vs room mix over various instruments inevitably raise some questions. Can all these musicians be happy with one and the same room, despite the very different audibility of the room's response? If not – what would be a more proper mix? Violin and viola players receive less than 10% of the total sound energy from the room, suggesting that these instruments could do with some room strength (G_{rev}).

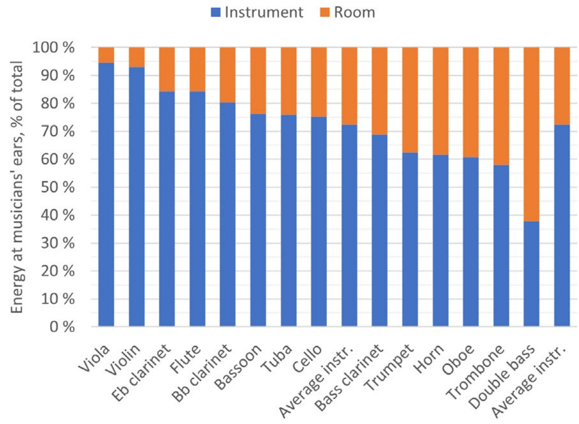

Figure 6. Energy components, in percentages at musicians' ears, from classical theory.

11. NOISE & HEALTH

Noise & Health issues regulations vary globally. Some work environment regulation limits do not include the sound from own activity, some limits apply to SPL measured in free-field, some regulations include limits for $L_{pA,max}$ and some include limits for $L_{pC,peak}$. Permissable daily dose of sound exposure is commonly defined to $L_{pA,eq8h} = 85dB$. Solitary practice, orchestra rehearsals and performances add up to a considerable sound exposure during a professional musicians life.

In any considerations of musicians' sound exposure, it would be important to know its principal sources. Figure 7 shows sound exposure per hour from instument and room, related to permissable daily dose, when playing with intensites similar to those during O'Briens measurements on 23 minutes of solitary practice, SPLs given in Table 1. The blue bars indicate the exposure from the instrument itself, i.e. the dry component, while the red extensions on top indicate the exposure from the room, i.e. reverberant sound.

The flute players would reach 100% of their daily permissible dose after one hour, while trombone, Eb-clarinet and trumpet would exceed their daily doses by some 20-60%. Note that the players of the brass instruments trombone, trumpet and horn receive a major part of their total sound exposure from the room. This suggests that these players could benefit from a room with less sound strength (G_{rev}).

In contrast, violas, oboes, cellos, and double basses reach less than 15% after one hour, meaning they are free to continue with similar intensity for several hours without exceeding the daily permitted dose. Moreover, the latter instruments could be practiced in more reverberant rooms, i.e. with stronger G_{rev}, and still be less exposed than the average instrument.

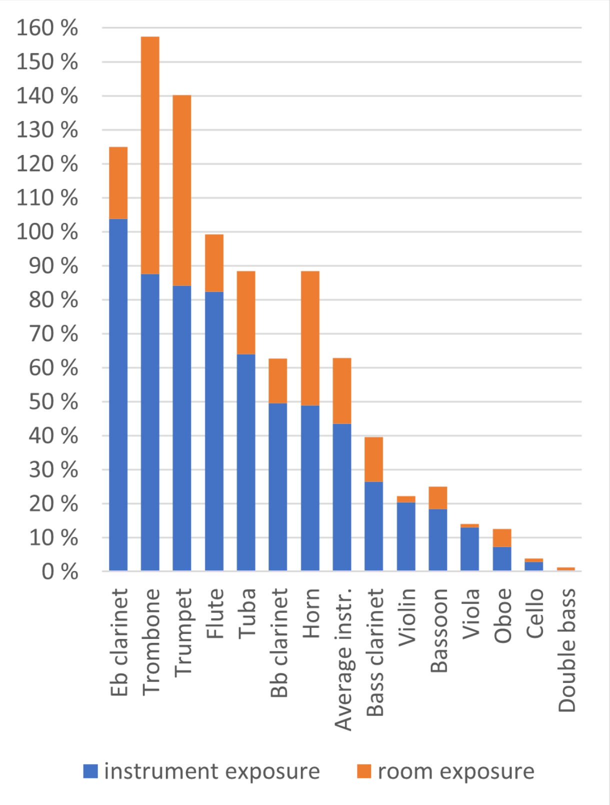

Figure 7. Sound exposure per hour from instument and room, related to permissable daily dose.

12. SUPPLEMENT TO ISO 23591

In prediction of total SPLs at the ears of musicians in solitary practice or rehearsal sessions, it is necessary to know the Dry component and the Room component. ISO 23591 presents sound power levels (unweighted) at *forte* and a calculation scheme for the room component.

In Table 4, $L_{pA,dry,ears} - L_{wA}$ is calculated from O'Briens measurements with classical theory, L_w is un-weighted sound power level at *forte* from ISO 23591 Annex A, and $L_{pA,dry,ears}$ is the result from the former two. Note that the table for simplicity presents the average L_{pA} from left and right ear. A more detailed table could include the difference between the ears.

The instruments are those present in both the ISO Annex table and in O'Brien's measurement report.

Table 4. Rightmost column, the dry components at musicians' ears (average left and right) from own instrument when playing at *forte*, with sound power levels L_w from ISO 23591 Annex A.

Instrument	$L_{pA,dry,ears} - L_{wA}$ [dB]	L_w [dB]	$L_{pA,dry,ears}$ [dB]
Bass clarinet	-5	92	87
Bass trombone	-7	105	98
Bassoon	-3	93	87
Bb clarinet	-2	93	91
Cello	-3	90	87
Double bass	-11	92	81
Flute	-1	91	90
Harp	-3	92	89
Horn	-6	102	96
Oboe	-6	93	87
Piccolo	0	95	95
Snare drum	-5	101	96
Trombone	-7	104	97
Trumpet	-6	101	95
Tuba	-3	104	101
Viola	4	87	91
Violin	3	89	92

Note that both L_w and $L_{pA,dry,ears} - L_{wA}$ at *forte* depend on both musical strength and individual style of playing, since instrument directivity depends on frequency content, especially in wind instruments, introducing uncertainties. E.g., the L_w values in Table 4 are on average 3dB higher (±4dB) than those from the typical practice session, with 6dB stronger tuba and 4dB softer flute than in the data from the

typical practice session reported in this paper. See Figure 8 for details.
Figure 9 shows an example of varying sound radiation from bassoon, two trials, two players playing tuning notes at p, mf, f and ff. Horizontal axis is A-weighted SPL at 1.5m distance and vertical axis is the difference between A-weighted SPL at the ears of the bassoonist and A-weighted SPL at 1.5m. The diagram indicates that the variation from one musician to another can be bigger than the variation over dynamic levels.
In further work, these uncertainties will be studied further.

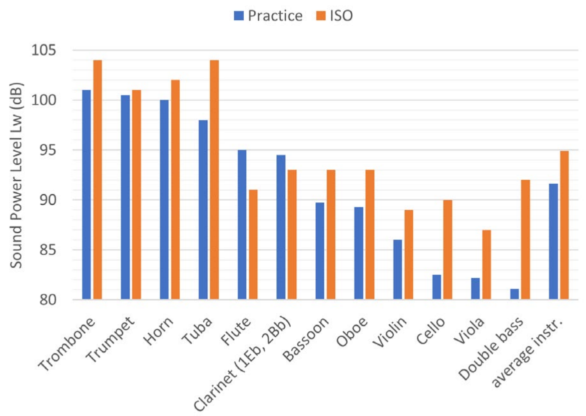

Figure 8 Sound Power Levels, Lw (dB), calculated from typical practice session reported in this paper, and at *forte* from ISO 23591.

Note on the weighting of L_w: Sound power levels in ISO 23591 at *forte* are un-weighted and could therefore be more influenced by low frequency power than the A-weighted sound power levels deduced from O'Brien's typical practice session. However, at forte, emitted sound power from most instruments have a relatively weak low frequency content, and thus the difference between L_w and L_{wA} would be negligeable. In low-pitched instruments like Double Bass, Tuba, Contra Bassoon, etc, the use of L_w values from ISO 23591 could lead to slightly overestimated A-weighted SPLs (dry, room and total).
Importantly, the "transfer function" in Table 4, $L_{pA,dry,ears} - L_{wA}$, is in itself not affected by the aforementioned frequency weighting in ISO.

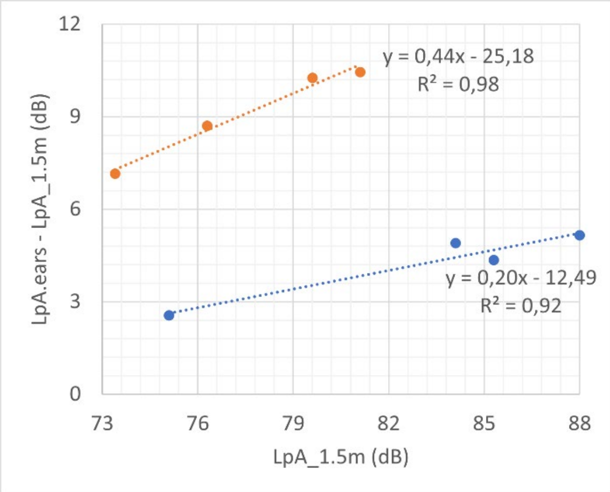

Figure 9 Sound radiation from bassoon, two players playing tuning notes at p, mf, f and ff.

13. SOUND EXPOSURE AT FORTE

13.1 Solitary practice in a room with arbitrary volume and reverberation time

Total A-weighted sound pressure levels at the ears of a musician during solitary practice, playing at *forte*, can be calculated from (1) with the proper insertions of (2), (3) and (4), where L_w and $L_{pA,dry,ears}$ is given in Table 4, V is the volume of the room, in m^3, and T is the reverberation time in the practice room, in seconds.

$$L_{pA,ear} = 10 \cdot log\left(10^{\frac{L_{dry}}{10}} + 10^{\frac{L_{rev}}{10}}\right) \quad (1)$$

$$L_{dry} = L_{pA,dry,ear} \quad (2)$$

$$L_{rev} = L_w - 31 + G_{rev} \quad (3)$$

$$G_{rev} = 10 \cdot \log\left(31200 \cdot \frac{T}{V}\right) \quad (4)$$

13.2 Solitary practice in a room with volume 54m^3 and reverberation time 0.5s, at *forte*

In a practice room with T=0.5s and V=54m3, it follows from (4) that G_{rev}= *24.6dB* and from (3) that $L_{rev}=L_w$-*6.4dB*. Then $L_{pA.ears}$ is given from (1) by inserting L_{rev} and using L_w and L_{dry} for the various instruments playing at *forte* from Table 4. Resulting LpA.ears and permissible duration for 17 different instruments played at *forte* are given numerically in Table 5, and graphically in Figure 10.

Permissible durations at these levels are based on the assumption of a permissible daily dose equivalent to LpA.eq.8h=85dB and calculated from

$$t_{lim}\ [minutes] = 8{\cdot}60{\cdot}10^{\,0.1\cdot(85-L_{pA.ears})} \qquad (5)$$

Table 5 A-weighted sound pressure levels, average over left and right ears of a musician during solitary practice, and permissible duration, playing an instrument at *forte*.

	LpA.ears *[dB]*	Permissible duration *[minutes]*
Tuba	103	8
Bass trombone	101	11
Trombone	100	14
Horn	99	20
Snare drum	98	22
Trumpet	98	25
Piccolo	96	39
Violin	92	86
Bb clarinet	92	88
Viola	91	110
Flute	91	118
Harp	91	131
Bassoon	90	158
Oboe	90	158
Bass clarinet	89	176
Cello	89	208
Double bass	87	310

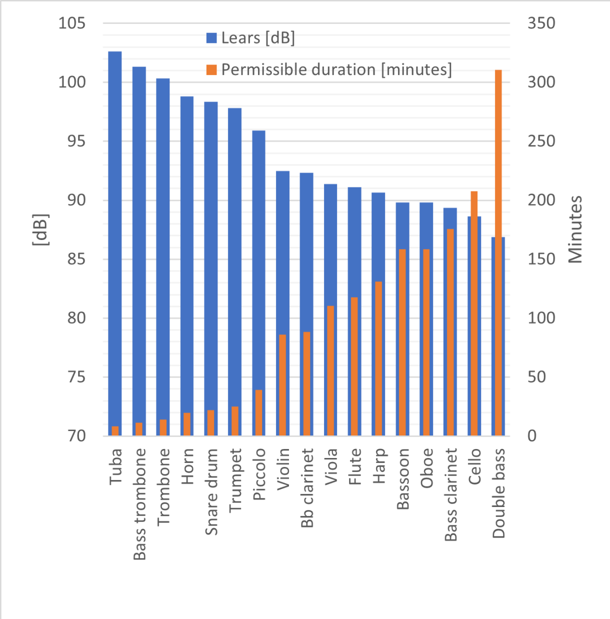

Figure 10 Graphical presentation of exposure levels and duration limits given in Table 5.

Like in Figure 10, bars in Figure 11 indicate the exposure levels given in Table 5, only that the bars vertically divided in the two components contributing to the exposure, namely the Instrument component, i.e. the Dry component, and the Room component.
The lower, blue bars indicate the exposure that would occur in a nearly an-echoic environment, like out-doors or in a very dry or very large room.
The red bars stacked on to of the blue bars alone indicate the extra sound exposure due to the room acoustics of the practice room in the example. The top edge of the stacked bars indicates the total sound exposure level, $L_{pA.ears}$, being the sum of the two components, Instrument and Room.

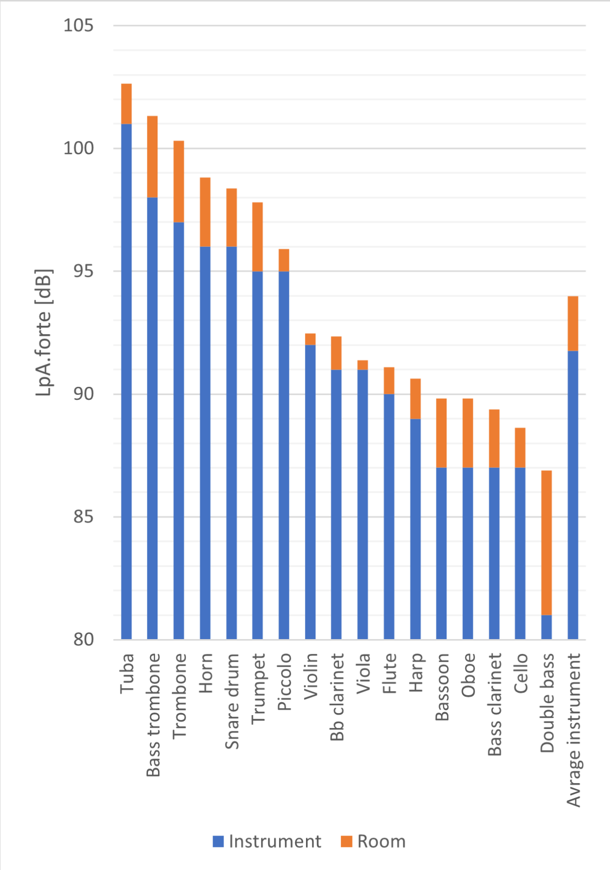

Figure 11 A-weighted sound pressure levels at ears (average of left and rright ears) of the musician during solitary practice in a 54m3 practice room with 0.5s reverb time, playing forte, various instruments; Dry component from the instrument (blue bars) and addition due to reflectded sound (Room, red extensions on top).

13.3 Ensemble play in rehearsal and performance.

SPL from own instrument and room in ensemble play can be calculated from (1) by replacing L_{rev} with L_p from formula (A.1) in Annex A of ISO 23591. Note that this does not include dry components from other instruments. Sound components and total SPL in ensemble play have been addressed by Skålevik [2][3] and Wenmaekers [4].

14. FURTHER WORK

In further work, similar measurements and calculations should be performed with the intension to extend the list of data in Table 4, to include more of the instrument types given in Table A.1 in Annex A of ISO 23591, but also to verify data in current work. While this paper is written, a Master Thesis suggested and supervised by this author, is being written at NTNU, Trondheim, Norway, reporting from detailed measurements on clarinet players during solo play in an anechoic chamber as well as in a practice room.

The repeatability and the dependency of dynamics and individual style of playing, on the relationship between source power and directivity, is critical for the Dry component and will be addressed.

Moreover, with the extended data on the Dry Self component, further investigations on the preferred balance between sound components from instruments, from room, and from others (in ensemble play) would provide further useful insight in music room acoustics.

All data in this paper, including L_w -values in ISO, should be tested and verified based on more measurements, including an extended list of instruments.

15. ACKNOWLEDGEMENTS

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16. SUMMARY

In current work, the relationship between the sound power level from musical instruments and the dry component of sound pressure levels at the corresponding musician's ears have been calculated from measurements with two different methods, 1) simulations in a 3D model and 2) with classical theory, described in this paper. The two methods produced practically similar results. ISO 23591 Annex A provides a method to calculate SPL of reverberant sound produced by musical instruments playing at forte in rehearsal rooms. In this paper it has been shown that without including the dry component the actual total SPL at musicians' ears will be underestimated by 1-14dB, depending on instrument type. Dry components for 17 instrument types played at forte, together with formulas to calculate the total SPL, are presented. Results indicate that brass instruments may benefit from less reflected sound (G_{rev}), while violin and viola may benefit more, than the average instrument. A supplement to the information in ISO 23591 Annex A with formulas and descriptions for computing the total SPL at musician's ears during solitary practice as well as group rehearsals is presented.

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