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Binaural sound exposure by the direct sound of the own musical instrument

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ABSTRACT

The amount of sound exposure of musicians within a symphonic orchestra is dependent on a large number of aspects. Among these aspects are the many different musical instruments and the impact of room acoustics by the reflected sound. However, it is impossible to obtain separately the contribution of each different aspect from the individually measured sound exposure. Therefore a sound level prediction model was proposed based on measured directivity and sound power of musical instruments and measured $ST_{\text{early,d}}$ and $ST_{\text{late,d}}$ (Early and Late Support parameter) over various distances. As part of this model, the sound level at the ears caused by the direct sound of the own musical instrument is estimated using the directivity and sound power measured in the free field at a distance of more than 2 m combined with the distance and angle between the musician's ears and its own musical instrument. To validate this method, binaural sound levels have been measured in an anechoic room while playing the flute, trumpet, trombone and violin. Also, a reference sound level measured in front of the musician at 2 m distance was used to calibrate the model. It was found that the model can predict the binaural sound level by the direct sound of the own musical instrument within 1 dB(A) accuracy; also interaural level differences have been measured up to 7 dB(A). However, estimating the average distance and angle between the acoustical centre of the musical instrument and the individual ears is not always straightforward.

1 INTRODUCTION

A sound level prediction model is under development in order to study the distinct contribution of direct and reflected sound per musician within a symphonic orchestra to the sound exposure of each individual musician within the orchestra. The model is introduced by Wenmaekers et al.^{1,2} and an update will be summarized in section 2. A part of this prediction model describes the direct sound level of the musicians own instrument, which can be determinative for the total sound exposure of orchestra musicians as proposed by Schmidt.³ He also concluded that sound exposure measurements should be performed at both musicians ears. In this paper, the validity

of the proposed prediction model for the sound level of the own instrument is investigated using binaural sound level measurements in an anechoic room, while playing the flute, piccolo flute, trumpet, flugelhorn, bass trombone, trombone and violin. The sound level prediction model will be treated in section 2 and the validation study is treated in section 3.

2 SOUND LEVEL PREDICTION MODEL

The receiving sound levels of different musicians in a symphonic orchestra at a musicians' or conductors' position depend on many aspects. For every receiver the energy as well as frequency balance of the sound levels is different. When only considering acoustical aspects, and discarding musical aspects, the sound level of a single sound source at a receiver position can be described using the properties of the sound source, the sound path and the receiver. The model which is proposed hereafter is summarized in figure 1.

2.1 Sound source

In general a sound source can be described by the sound intensity $L_I(f, \varphi, \theta, d)$ which is frequency (f), orientation (elevation φ and azimuth θ) and distance (d) dependant. However, a musical instrument can not easily be defined by these parameters, because the spectrum and directivity may change per note and playing style. When assessing sound levels, one is often interested in an average value over time. It may then be legitimate to use average values. In this model, measured average values of sound intensity $L_I(f, \varphi, \theta)$ for common orchestral instruments at free field distance are used from Pätynen & Lokki.⁴ To asses spectral and loudness differences between instruments the sound power L_w is needed, which is derived from calibrated anechoic recordings of musical pieces by Pätynen et al..⁵

2.2 Sound path

The transfer of sound from a sound source to a receiver in a room can be fully described by the room impulse response, which can either be measured or predicted. However, in case of a

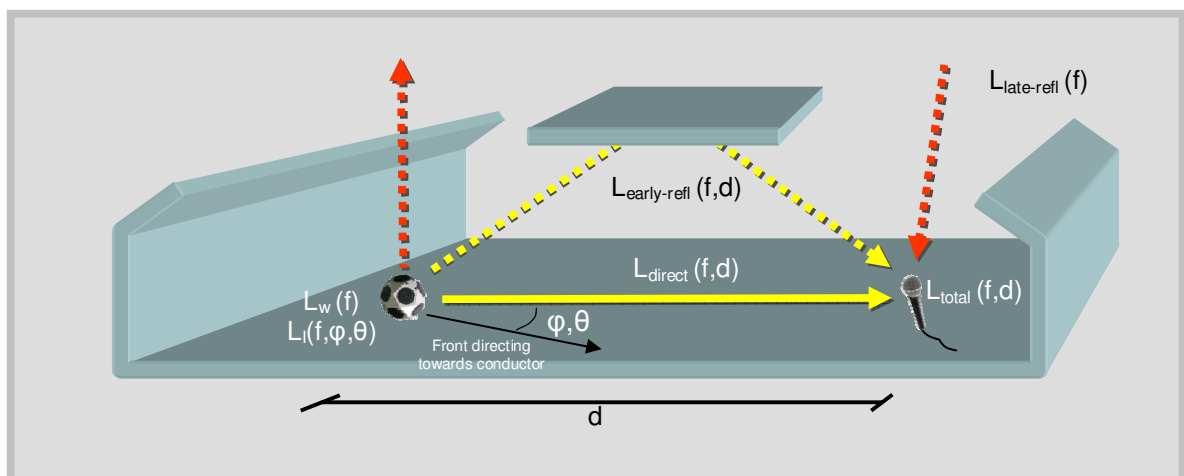


Figure 1: summary of the source – receiver model.

musical instrument this implies that the impulse response should be determined using a sound source with the average directivity properties for every musical instrument. Also, the impulse response must be determined under the same conditions of a concert or rehearsal, which implies that the orchestra and/or audience must be taken into account.

In this model, the impulse response is divided in three typical room acoustical aspects to study the balance between them: the direct sound, the early reflected sound and the late reflected sound. The direct sound path is of interest to study the influence of available space and screens. The early reflected sound is generally considered to be meaningful for ensemble playing on stage while the late reflected sound may contribute to a sense of feedback from the hall.⁶ The direct sound is calculated analytically so that the influence of directivity of the sound source and the obstruction of the orchestra can be integrated. The early and late reflected sound energy is estimated from (measured) room impulse responses using an omnidirectional sound source on an empty stage. At the moment, there is no method available to translate these values so that source directivity and orchestra attenuation can be integrated.

2.3 Direct sound of other musician's instruments

The direct sound path depends on the source-receiver distance and orientation of the source relative to the receiver, assuming that the source musician is looking into the conductors' direction. Besides that, the attenuation of the orchestra is included from measured values of $\Delta L(f)$ by Dammerud and Barron.⁷ L_{direct} is then determined from equation 1 and 2:

$$L_{direct}(f_{oct}, d) = L_{eq;1m}(f_{oct}, \varphi, \theta) - 20\lg(d) + \Delta L(f_{oct}, d) \quad (1)$$

$$\Delta L(f_{oct}, d) = a(f_{oct}) \cdot d + c(f_{oct}) \quad (2)$$

where, $L_{eq;1m}(f, \varphi, \theta)$ is the sound level in dB at 1 meter distance per frequency band in Hz at elevation φ and azimuth θ in degrees estimated from measured values of sound intensity $L_i(f, \varphi, \theta)$ and $L_{eq;1m;front}(f)$ derived from the frontal anechoic recordings of every instrument; d is the source receiver distance in meters; and $\Delta L(f)$ is the attenuation by the orchestra in dB estimated from measurements by Dammerud and Barron⁷ using an attenuation factor 'a' in dB loss per meter through the orchestra and a constant 'c' in dB for the overall shift of attenuation due to the effect of the floor and orchestra reflections, see table II in reference 7.

2.4 Direct sound of the own instrument

The direct sound level of the own instrument is modelled by using a different distance and angle between the sound source and each ear. However, the available sound intensity per angle $L_i(f, \varphi, \theta)$ has been determined using the musicians head in the centre⁵. In our model, a reference point on the musical instrument itself needs to be regarded as the point source, even though the musicians' ear is in the near field of the musical instrument within less than 1 meter distance. For each individual ear, the direct sound of the own instrument for each ear is calculated by:

$$L_{direct,own}(f_{oct}, d) = L_{eq;microphone}(f_{oct}, \varphi, \theta) - 20\lg\left(\frac{d;instrument_to_ear}{d;microphone_to_instrument(\varphi, \theta)}\right) \quad (3)$$

Note that, ' $d;microphone_to_instrument$ ' is the distance between the microphone position and the reference point on the musical instrument, which depends on the angles φ and θ .

2.5 Early reflected sound

The early reflected sound level $L_{early-refl}$ is estimated from the sound power L_w of the instrument and the measured Early Support at various distances d denoted $ST_{early;d}$ as introduced by Gade⁸ and modified by Wenmaekers et al.⁹, see equation 4.

$$ST_{early;d} = 10 \lg \left(\frac{\int_{10}^{103-delay} p_d^2 dt}{\int_0^{10} p_{1m}^2 dt} \right) \quad (4)$$

Where, $ST_{early;d}$ is the Early Support at distance d in meters; p_d is the sound pressure measured at distance d ; p_{1m} is the sound pressure measured at 1 m distance; and delay is the source-receiver distance divided by the speed of sound.

The early reflected sound level $L_{early-refl}$ is then determined using equation 5.

$$L_{early-refl}(f_{oct}, d) = L_w(f_{oct}) + ST_{early;d}(f_{oct}, d) - 31 \quad (5)$$

where, $L_w(f)$ is the sound power in dB per frequency band in Hz estimated from measured values for every instrument derived from anechoic recordings by Pätynen et al..⁵

2.6 Late reflected sound

The late reflected sound level $L_{late-refl}$ is determined from the sound power L_w of the instrument and the Late Support at various distances d denoted $ST_{late;d}$ as introduced by Gade⁸ and modified by Wenmaekers et al.⁹, see equation 6 and 7. The $ST_{late;d}$ is not dependant on the source to receiver distance, so a fixed value per stage can be used.

$$ST_{late;d} = 10 \lg \left(\frac{\int_{10}^{\infty} p_d^2 dt}{\int_0^{10} p_{1m}^2 dt} \right) \quad (6)$$

$$L_{late-refl}(f_{oct}) = L_w(f_{oct}) + ST_{late;d}(f_{oct}) - 31 \quad (7)$$

To reduce the measurement uncertainty of $ST_{early;d}$ and $ST_{late;d}$ it is recommended use to an average value over 5 stepwise rotations of the omnidirectional sound source¹⁰ and to measure impulse responses with a decay range INR¹¹ of at least 45 dB.

2.7 Receiver

The ears are highly sophisticated sound receivers, with varying sensitivity to frequency and directionality towards the viewing direction. The varying sensitivity is introduced in this model by A or C weighting the sound level. However, the model can also be used to consider separate frequency bands. So far, varying (receiver) sensitivity with respect the directional hearing is not taken into account by the model.

3 SOUND LEVEL MEASUREMENTS

3.1 Method

The direct binaural sound level of the own instrument is measured in an anechoic room with two DPA 4060 miniature condenser microphones fixed in front of the musicians' ears, see figure 2. Also, a B&K type 4189-A-021 microphone is positioned at 2 meters distance from the musicians' ears at equal height, see figure 2 denoted Ref, to determine the reference sound level in front of the musician $L_{eq,microphone}(f)$, see equation 3. The sound pressure levels measured using the DPA microphones were corrected to match the flat frequency response of the B&K microphone based on a comparison study of the microphones in a diffuse field (reverberation room) and direct field (anechoic room). However, it should be noted that a proximity effect occurs when the DPA microphones are positioned in front of the musicians' ear. It was found that for both microphones the sound levels measured close to the ear are 2.5, 4.5 and 2.0 dB higher in the octave bands 2, 4 and 8 kHz respectively. These differences are considered to be caused by the sound field, and not by the type of microphone, so no additional correction is made.

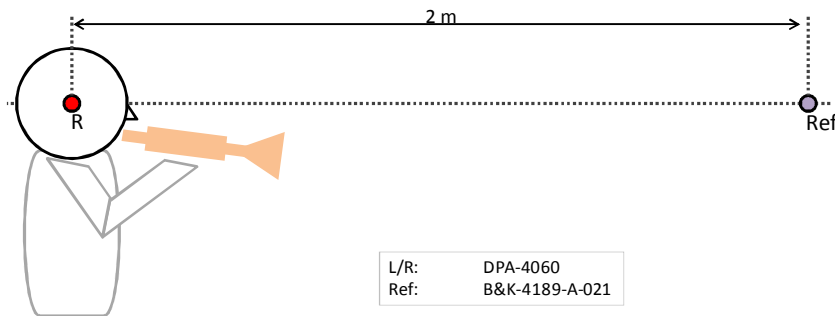


Figure 2: top view (left) and side view (right) of the microphone setup.¹²

3.2 Procedure

Nine different musical instruments played by five different musicians were investigated in the research: flute (2x), piccolo (2x), trumpet, flugelhorn, bass trombone, trombone and violin. Every musician was asked to play C major scales in the native playing range of the instrument over two octaves up and down, with altered articulation (staccato and legato) and musical dynamics (piano and forte). All tones were played with constant speed. While playing, calibrated recordings have been made using the three microphones and Dirac measurement software. The average sound pressure level was determined for the whole recording session. Afterwards, the background noise level of the measurement system was determined. In this research, sound levels are only presented if they are at least 10 dB above the background noise level.

3.3 Distance between instrument and ears

Part of the models' input in equation 3 are the geometrical parameters elevation φ , azimuth θ and distance between the instrument and the musicians left and right ear. The applied angles of elevation φ and azimuth θ are illustrated in figure 3. The values determined for the musicians in this research are presented in table 1. For the (transverse) flute, the geometrical parameters were determined relative to half of the tube length at 40 cm to the left ear and 20 cm to the right ear and at 28 cm to the left ear and 15 cm to the right ear for the piccolo. For the trombone players' right ear, the geometrical parameters were determined relative to the bell, slightly on the left at 50 cm. The trombone players' left ear is in close proximity to the tubes on the shoulder, which also radiates sound, so the geometrical parameters were determined relative to 30 cm. For both ears of the trumpet/flugelhorn player, the geometrical parameters were determined relative to the bell in front of the player at 55 cm. For the violin, the geometrical parameters were determined relative to the bridge, more or less in the middle of the soundboard at 20 cm to the left ear and 25 cm to the right ear. The neck of the violin was pointing towards 330 degrees azimuth.

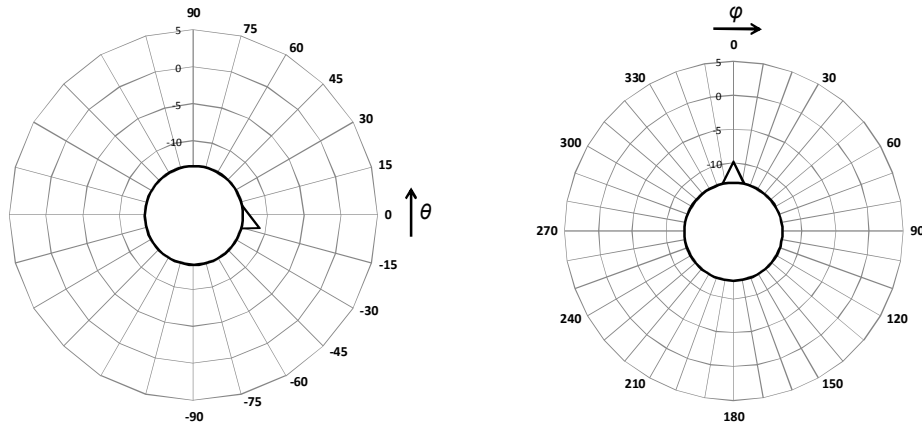


Figure 3: side view showing *Elevation* θ (left) and top view showing *Azimuth* φ (right).¹⁰

Table 1: geometrical parameters for the distance between instrument and ears.

Instrument	Elevation θ [°]	Azimuth φ [°]	D1* [m]	D2** [m]
Flute (L)	10	260	0.30	0.40
Flute (R)	10	250	0.30	0.20
Piccolo (L)	10	260	0.16	0.28
Piccolo (R)	10	250	0.16	0.15
Trumpet/ Flugelhorn (L&R)	0	180	0.55	0.55
(Bass) Trombone (L)	10	180	0.40	0.30
(Bass) Trombone (R)	10	150	0.40	0.50
Violin (L)	30	180	0.20	0.20
Violin (R)	30	135	0.20	0.25

* Distance between middle of the head to the reference point on the musical instrument

** Distance between ear to the reference point on the musical instrument

3.4 Results binaural measurements

Table 2 shows the measured level difference in dB between the left and right ear per instrument. The results are presented per un-weighted octave band and per A-weighted broadband. For reference, the absolute A-weighted sound level is also presented, which shows that the direct sound of the sound instrument is above 90 dB(A) in most cases, and even up to 100 dB(A) in one case. The A-weighted sound level difference at the two ears varies from -3.4 to -7.4 dB for the flutes and piccolos positioned on the right side of the head. For the trumpet and flugelhorn, a +0.7 dB and -1.7 dB A-weighted difference is found respectively, caused by the bells being slightly off centre to the left for the trumpet and to the right for the flugelhorn. A striking +4.7 and +4.9 dB A-weighted difference is found for the trombones, with differences of +11 to +14 in the high frequency bands. For the violin, an A-weighted level difference is found of +2.3 dB, which was expected to be (much) higher.

Table 2: Measured sound levels per instrument, difference left and right ear

	125	250	500	1000	2000	4000	8000	A-weighted		
	L-R	L-R	L-R	L-R	L-R	L-R	L-R	L	R	L-R
Flute 1		-2	-6	-7	-1	+1		86	93	-6.4
Piccolo 1			-4	-10	-1	-9	-6	90	93	-3.4
Flute 2		-3	-6	-8	-4	-3		86	93	-7.4
Piccolo 2			-5	-13	-2	-8	-9	92	97	-4.3
Trumpet	+1	+1	+1	-1	+3	+3	+4	97	96	+0.7
Flugelhorn	0	0	0	-2	-1	-2		98	100	-1.7
Bass trombone	+3	+3	+4	+6	+13	+12		96	91	+4.9
Trombone	+2	+3	+3	+6	+11	+14		97	92	+4.7
Violin	-1	0	+1	+4	0	0	+4	92	90	+2.3

Interaural level differences (ILD) have been reported earlier by Meyer¹³ (measured in an anechoic room) and Schmidt³ (measured in a rehearsal room). Schmidt reported a level difference of -7.4 dB for the flute and -6.7 for the piccolo. For the trumpet, values of 0 dB and +1.4 dB were reported by Meyer and Schmidt respectively, and for the trombone +3 dB and +3.8 dB. These values are (more or less) similar to what was found in this study. It is striking though, that Meyer and Schmidt found a level difference for the violin of +10 and +5.3 dB respectively, which is much higher than the +2.3 dB that was found in this study. But, it should be noted that the playing style of the violin player has large influence on the ILD. Using the model as presented in paragraph 2.4 we estimated that the ILD is +2.3 dB when the neck of the violin is pointing towards 330 degrees azimuth and the ILD is estimated to be + 8 dB when the neck of the violin is pointing towards 270 degrees azimuth!

3.5 Results model calculations

Using the sound level measured in front of the musician at 2 m distance; the directivity per angle from Pätynen & Lokki⁴; and the geometrical parameters as presented in table 1, the sound level at the musicians' ears have been estimated by equation 3. The results are compared to the actually measured sound levels. The difference between the measured and estimated values are presented in table 3a for the left ear and table 3b for the right ear. The results are presented per octave band and A-weighted. For reference, the absolute A-weighted sound level is also presented. In the column to the right, the A-weighted difference between measured and estimated is presented.

Table 3a: Binaural Sound Exposure: difference between measured and estimated, left ear

	125	250	500	1000	2000	4000	8000	A-weighted		
	L	L	L	L	L	L	L	Meas	Estim	M-E
Flute 1		3	9	-2	-1	0		86	87	-0,7
Piccolo 1			-1	-2	3	-7	-5	90	88	1,7
Flute 2		6	7	-4	-5	-1		86	89	-3,7
Piccolo 2			0	-2	4	-4	-5	92	89	3,3
Trumpet	0	-1	3	-6	3	2	0	97	99	-2,2
Flugelhorn	0	0	4	-3	0	0		98	100	-2,1
Bass trombone	-3	-4	-1	-2	4	-1		96	97	-1,4
Trombone	-3	-2	-1	0	5	2		97	97	-0,4
Violin		2	8	-2	-1	-1	8	92	93	-0,9

Table 3b: Binaural Sound Exposure: difference between measured and estimated, right ear

	125	250	500	1000	2000	4000	8000	A-weighted		
	R	R	R	R	R	R	R	Meas	Estim	M-E
Flute 1		-1	9	0	-5	-6		93	93	-0,1
Piccolo 1			-3	2	-1	-3	-4	93	93	-0,3
Flute 2		2	6	-3	-7	-3		93	95	-2,2
Piccolo 2			0	5	1	-2	-2	97	94	2,2
Trumpet	-1	-2	2	-4	0	-1	-3	96	99	-2,8
Flugelhorn	0	0	5	-1	0	3		100	100	-0,5
Bass trombone	-2	-3	-2	-4	-5	-8		91	93	-2,7
Trombone	-1	-2	-1	-3	-2	-6		92	94	-1,5
Violin		4	7	-4	1	3	6	90	91	-1,0

The comparison of the measured and estimated binaural sound levels shows that, for the individual frequency bands, errors are found up to 9 dB. The mean absolute error is approximately 3 dB for the individual frequency bands. For most instruments, both positive and negative errors occur over the frequency range, except for the trombones at the right ear that show only negative errors. When looking at the A-weighted errors, for the left ear, the model overestimates the A-weighted level by 0.7 to 3.7 dB. For the right ear, the model overestimates the A-weighted level between 0.1 and 2.8 dB. Exceptions are the piccolos that are underestimated by 1.7 to 3.3 dB.

4 CONCLUSIONS

Looking at the individual frequency bands, we can conclude that the model is accurate within +/- 10 dB. This large uncertainty can be caused by the fact that the musician's ear is that close to the musical instrument, that the instrument cannot be considered as a point source. Also, the directivity that is used in the model was obtained from different instruments playing a different repertoire. Additional measurements with multiple musicians and instruments could produce more uniform results. However, considering the model's purpose being to investigate the different contributions of many different aspects to the total noise exposure of musicians within an orchestra, we can conclude that the prediction of the direct sound exposure of the own instrument at the musician's ear can be done almost within +/- 4 dB uncertainty.

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