Room Acoustics

Hearing is Believing?

Measuring is Knowing?
Sound Levels on Stage
Measurements and Predictions

Remy Wenmaekers
TU/e, Level Acoustics & Vibration
Measurements of sound levels

High strings
75 - 95 dB(A)

Low strings
75 - 90 dB(A)

Brass instr.
Wind instr.
Percussion
80 - 95 dB(A)

TABLE II. Summarized data for all readings, 2004–2007.

<table>
<thead>
<tr>
<th>Position</th>
<th>dBAL Eq mean</th>
<th>dBAL range</th>
<th>dBC peak</th>
<th>dBC median</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Violin 1</td>
<td>84.4</td>
<td>77.4–90.6</td>
<td>119.6</td>
<td>107.1–131.2</td>
<td>24</td>
</tr>
<tr>
<td>Violin 2</td>
<td>84.7</td>
<td>78.7–90.7</td>
<td>118.1</td>
<td>105.1–130.2</td>
<td>12</td>
</tr>
<tr>
<td>Viola</td>
<td>85.3</td>
<td>76.1–94.9</td>
<td>123.2</td>
<td>106.5–132.8</td>
<td>84</td>
</tr>
<tr>
<td>Cello</td>
<td>84.5</td>
<td>76.2–89.3</td>
<td>121</td>
<td>116.7–131.3</td>
<td>63</td>
</tr>
<tr>
<td>Bass</td>
<td>84.3</td>
<td>78.1–91.7</td>
<td>121</td>
<td>116.7–131.3</td>
<td>63</td>
</tr>
<tr>
<td>Harp</td>
<td>85.2</td>
<td>77.3–90.5</td>
<td>110.8</td>
<td>100.8–120.4</td>
<td>48</td>
</tr>
<tr>
<td>Flute 1</td>
<td>87.8</td>
<td>78.1–93.1</td>
<td>135.3</td>
<td>126.1–138.3</td>
<td>128</td>
</tr>
<tr>
<td>Flute 2/Piccolo</td>
<td>88.2</td>
<td>80.2–94.4</td>
<td>132.5</td>
<td>122.5–144</td>
<td>63</td>
</tr>
<tr>
<td>Oboe 1</td>
<td>87.1</td>
<td>80.5–91.5</td>
<td>116.8–130.4</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Oboe 2/Cor Anglais</td>
<td>87</td>
<td>81.3–92.3</td>
<td>111.8–130.4</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Clarinet 1</td>
<td>88.5</td>
<td>80.4–93.9</td>
<td>116.6</td>
<td>109.1–131.3</td>
<td>63</td>
</tr>
<tr>
<td>Clarinet 2/bass clarinet</td>
<td>86.6</td>
<td>79.8–91.7</td>
<td>127.2</td>
<td>116.7–131.3</td>
<td>63</td>
</tr>
<tr>
<td>Bassoon 1</td>
<td>87.7</td>
<td>79.9–93.2</td>
<td>126.1</td>
<td>115.3–138.3</td>
<td>63</td>
</tr>
<tr>
<td>Bassoon 2/contra bassoon</td>
<td>87.5</td>
<td>79.7–94.4</td>
<td>125</td>
<td>116.7–131.3</td>
<td>63</td>
</tr>
<tr>
<td>Trumpet 1</td>
<td>89.3</td>
<td>82.1–95.1</td>
<td>132.5</td>
<td>122.5–144</td>
<td>63</td>
</tr>
<tr>
<td>Trumpet 2</td>
<td>88.9</td>
<td>80.2–95.3</td>
<td>132.5</td>
<td>122.5–144</td>
<td>63</td>
</tr>
<tr>
<td>Trumpet 3</td>
<td>87.9</td>
<td>79.7–93.6</td>
<td>125.3</td>
<td>118.5–137.7</td>
<td>128</td>
</tr>
<tr>
<td>Horn 1</td>
<td>89.5</td>
<td>81.4–95.2</td>
<td>125.3</td>
<td>118.5–137.7</td>
<td>128</td>
</tr>
<tr>
<td>Horn 2</td>
<td>88.8</td>
<td>81.6–95</td>
<td>125.3</td>
<td>118.5–137.7</td>
<td>128</td>
</tr>
<tr>
<td>Horn 3</td>
<td>89.3</td>
<td>82.7–95.9</td>
<td>125.3</td>
<td>118.5–137.7</td>
<td>128</td>
</tr>
<tr>
<td>Horn 4</td>
<td>88.7</td>
<td>82.9–93.5</td>
<td>125.3</td>
<td>118.5–137.7</td>
<td>128</td>
</tr>
<tr>
<td>Trombone 1</td>
<td>88.1</td>
<td>82.4–94.1</td>
<td>125.3</td>
<td>118.5–137.7</td>
<td>128</td>
</tr>
<tr>
<td>Trombone 2</td>
<td>88.8</td>
<td>82.3–95.4</td>
<td>125.3</td>
<td>118.5–137.7</td>
<td>128</td>
</tr>
<tr>
<td>Bass trombone</td>
<td>87</td>
<td>80.9–93.6</td>
<td>113.2</td>
<td>104.9–128</td>
<td>63</td>
</tr>
<tr>
<td>Tuba</td>
<td>86.9</td>
<td>78.5–92.1</td>
<td>114.7</td>
<td>106.5–131.2</td>
<td>63</td>
</tr>
<tr>
<td>Percussion</td>
<td>88.8</td>
<td>81.5–96.1</td>
<td>132.5</td>
<td>122.5–144</td>
<td>63</td>
</tr>
<tr>
<td>Timpani</td>
<td>87.7</td>
<td>80.5–96.3</td>
<td>132.5</td>
<td>122.5–144</td>
<td>63</td>
</tr>
</tbody>
</table>

Total samples: 1608

[O'brien et al. (2008)]
• Orchestral musicians are exposed to equivalent sound levels above 85 dB(A), both during individual (often highest) and group rehearsals/performances.

• In the orchestra: ‘musicians feel their own instrument is not noisy, but it is the neighbouring instruments that cause the problems’ (Laitinen, 2005)
Orchestral musicians are exposed to equivalent sound levels above 85 dB(A), both during individual (often highest) and group rehearsals/performances.

In the orchestra: ‘musicians feel their own instrument is not noisy, but it is the neighbouring instruments that cause the problems’ (Laitinen, 2005)

Ear plugs hinder the musical performance and are only used occasionally.

Physical measures are often suggested when playing in the orchestra, such as more space, risers, screens and acoustic treatment.

But are these measures effective? Can we predict their (in)effectiveness?
Sound level prediction model

\[ L_{\text{direct}} : \text{direct sound level} \]
\[ L_{\text{early-refl}} : \text{early reflected sound level} \]
\[ L_{\text{late-refl}} : \text{late reflected sound level} \]
\[ L_{\text{total}} : \text{total sound level} \]
\[ (\text{total} = \text{direct, early and late}) \]

Wenmaekers, Hak (2015)
A sound level distribution model for symphony orchestras: Possibilities and limitations.
Psychomusicology: Music, Mind, and Brain 25(3) 219-233.
Sound level prediction model

**MUSIC**
- **Input**
  - music material
    - Anechoic recording per musician: $L_{\text{music}}(f)$
- **Databases**
  - distance ears to own instr.
  - angle ears to own instr.
- **Calculations**
  - For each musician:
    - Direct sound own
  - For each SR combination:
    - Direct sound others
    - Sum all others

**ORCHESTRA**
- **Input**
  - Anechoic recording per musician: $L_{\text{music}}(f)$
- **Databases**
  - X, Y, and Z coordinates
  - instrument type
  - define "orchestra edge area"
- **Calculations**
  - for each musician:
    - $L_{\text{direct, own}}(f)$
    - $(\text{binaural, } L/R)$
  - for each SR combination:
    - $L_{\text{direct, others}}(f)$

**ROOM ACOUSTICS**
- **Input**
  - sound source directivity
- **Calculations**
  - $\Delta L_{\text{ext}}(125 - 500 \text{ Hz})$
  - $\Delta L_{\text{ext}}(1 - 8 \text{ kHz})$

**ATTENUATION ORCHESTRA**
- **Input**
  - HRTF
- **Calculations**
  - for each musician:
    - $L_{\text{ext, own}}(f)$
    - $L_{\text{ext, others}}(f)$
  - for each SR combination:
    - $L_{\text{ext, others}}(f)$

**TOTAL SOUND LEVEL**
- **Input**
  - $L_{\text{sum}}(f)$
- **Calculations**
  - $L_{\text{total}}(f)$

---

Wenmaekers, Nicolai, Hornikx, Kohlrausch (2017)
Why orchestral musicians are bound to wear earplugs
Anechoic recordings of orchestral music
- Mahler Symphony no. 1 sample (2:12 min)

[J. Pätynen, V. Pulkki and T. Lokki 2008]
Orchestra setup

For $n$ musicians:
- X,Y, and Z coordinates
- instrument type

- define “orchestra edge area”
Distances and angles

- Right ear: 75 degrees elevation
- Left ear: 65 degrees elevation
- Both ears: 270 degrees azimuth

A or B is close to the acoustic centre
Directivity instrument and ear

Relative sound intensity $L_I(f, \varphi, \theta)$
Directivity of orchestra instruments in CLF format [Pätynen and Lokki 2010]
Directivity of the ear with microphones in front of a HATS [Wenmaekers, 2015]

Directivity only taken into account for direct sound
(for reflective sound, directivity is negligible)

Sensitivity of stage acoustic parameters to source and receiver directivity: Measurements on three stages and in two orchestra pits.
Why orchestral musicians are bound to wear earplugs


Wenmaekers, Nicolai, Hornikx, Kohlrausch (2017)

Sound level prediction model

MUSIC

- Anechoic recording per musician:
  - \( L_{\text{direct}}(f) \)

ORCHESTRA

- X, Y, and Z coordinates
- Instrument type
- Define "orchestra edge area"

ROOM ACOUSTICS

- Sound power
  - \( L_{\text{power}}(f) \)

Calculations

For each musician:
- Direct sound own
- Direct sound others
- Sum all others

For each SR combination:
- Interference floor reflection
- Sound attenuation orchestra

Output

For each musician:
- Direct sound level
  - Binural, L/R

- Total sound level
- Early reflected sound level
- Late reflected sound level

Databases

- Distance ears to own instr.
- Angle ears to own instr.
- Sound source directivity
- HRTF

Technische Universiteit Eindhoven
University of Technology
Time windows (18 x 12 m² stage)

Source Self
Source other 1
Source other 2
Source other n

Receiver Self

- Direct sound Self, time is 3 ms at 1 m distance
- Direct sound Others, +/- 3 to 60 ms after direct sound Self
- Early reflected Self, +/- 5 to 100 ms after direct sound Self
- Early reflected Others, +/- 5 to 100 ms after direct sound Self
- Late reflected Hall, +/- > 100 ms to infinite after direct sound Self


**Optimised acoustic parameters**

103 ms delay = time for direct sound to arrive at receiver

\[ ST_{early,d} = 101g \]

\[ ST_{late,d} = 101g \]

---


Sound level prediction model

Wenmaekers, Nicolai, Hornikx, Kohlrausch (2017)
Why orchestral musicians are bound to wear earplugs
Occupied stage, direct sound

**Attenuation of direct sound with floor reflection**

![Graph showing level relative to direct sound in dB vs. distance for different frequencies (500 Hz, 1000 Hz, 2000 Hz). The graphs show data points and trend lines for occupied stage measurements compared to literature trend lines.](image)

- **Diag/Side 500 Hz**
  - $a = -0.1$
  - $c = -1.6$
  - $R^2 = 0.03$

- **Diag/Side 1000 Hz**
  - $a = -0.9$
  - $c = 2.2$
  - $R^2 = 0.74$

- **Diag/Side 2000 Hz**
  - $a = -0.8$
  - $c = -0.4$
  - $R^2 = 0.55$

---

**References**

Occupied stage, reflected sound

How orchestra members influence stage acoustic parameters on five different concert hall stages and orchestra pits.
J. Ac. Soc. Am. 140(6), 4437-4448.
Sound level prediction model

Wenmaekers, Nicolai, Hornikx, Kohlrausch (2017)
Why orchestral musicians are bound to wear earplugs
For each musician:
- Direct sound own

For each SR combination:
- Direct sound others

Sum all others

\[ L_{\text{direct others}}(f) \]

(binaural, L/R)

\[ L_{\text{direct own}}(f) \]

\( \Delta L_{\text{orch}}(125 - 500 \text{ Hz}) \):
interference floor reflection

\( \Delta L_{\text{orch}}(1 - 8 \text{ kHz}) \):
sound attenuation orchestra

\[
L_{\text{direct}}(f, d) = L_{\text{eq,1m}}(f, \varphi, \theta) - 20 \log(d) + \Delta L_{\text{orch}}(f, d) + \Delta L_{\text{ear}}(f, \theta)
\]
Sound level prediction model

### Input
- **Music**
  - Music material
    - Anechoic recording per musician: $L_{\text{music},i}(f)$
  - Distance ears to own instr.
  - Angle ears to own instr.

### Databases
- **Orchestra**
  - Orchestral layout
    - For $n$ musicians:
      - X, Y, and Z coordinates
      - Instrument type
    - Define "orchestra edge area"
  - Sound source directivity
  - HRTF

### Calculations
- **Musician**
  - Attenuation orchestra
    - $\Delta L_{\text{attenuation}}$ (150 - 600 Hz): interference floor reflection
    - $\Delta L_{\text{attenuation}}$ (1 - 8 kHz): sound attenuation orchestra
  - Early refl. own
  - Early refl. others
  - Sum all others
  - Late refl. others
  - Sum all others

### Output
- **Direct sound level**
  - For each musician: $L_{\text{direct, own}}(f)$
  - For each SR combination: $L_{\text{direct, others}}(f)$

- **Reflected sound level**
  - Early reflected sound level:
    - For each musician: $L_{\text{early refl, own}}(f)$ (binaural, L/R)
    - For each SR combination: $L_{\text{early refl, others}}(f)$ (monaural, omnir)
  - Late reflected sound level:
    - Sum components
    - For each musician: $L_{\text{late refl}}(f)$ (monaural, omnir)

---

Wenmaekers, Nicolai, Hornikx, Kohlrausch (2017)
Why orchestral musicians are bound to wear earplugs
Early reflected sound:

\[ L_{\text{early-refl}}(f, d) = L_w(f) + ST_{\text{early};d}(f, d) - 11 \]

Late reflected sound:

\[ L_{\text{late-refl}}(f) = L_w(f) + ST_{\text{late};d}(f) - 11 \]

Sound levels on stage: Measurements and Predictions

Wenmaekers, Nicolai, Hornikx, Kohlrausch (2017)
Why orchestral musicians are bound to wear earplugs
Calculated sound levels

- A-weighted sound pressure level
- Received level at musicians’ ears
- Window 2k samples (fs=48kHz)
- Sound is anechoic, recorded by Pätynen et al.

https://youtu.be/30ql7slyql4
Validation

- $L_{Aeq}$ per 46 excerpts of the 2 minutes
- Example shown for cello and trumpet
- Trend and level for $L_{Aeq}$ well predicted
- Activity of trumpet player (and nearby instruments) visible as maxima

- $L_{Aeq}$ for the full movement (2 minutes), for three different stages, 65% of the positions are predicted within 2 dB deviation
State of the art

- Orchestral musicians are exposed to equivalent sound levels above 85 dB(A), both during individual (often highest) and group rehearsals/performances.

- In the orchestra: ‘musicians feel their own instrument is not noisy, but it is the neighbouring instruments that cause the problems’ (Laitinen, 2005)

- Ear plugs hinder the musical performance and are only used occasionally.

- Physical measures are often suggested when playing in the orchestra, such as more space, risers, screens and acoustic treatment.

But are these measures effective? Can we predict the (in)effectiveness?
Physical measures

• Available space

• Riser height

• Screens

• Acoustic conditions

A) a large screen positioned at 0.3 m behind musician
B) a hypothetical case with fully surrounding screens

reflected sound changed relative to a concert hall by
A) + 6 dB, similar to a small rehearsal room
B) – 6 dB, similar to a theatre stage with curtains

* Suggested in Dutch regulation
Results

For excerpt of Mahler Symphony 1

<table>
<thead>
<tr>
<th></th>
<th>higher/lower risers</th>
<th>more/less space</th>
<th>screens behind</th>
<th>screens surround</th>
<th>+6 dB reflected sound</th>
<th>-6 dB reflected sound</th>
</tr>
</thead>
<tbody>
<tr>
<td>high strings</td>
<td>+/- 0.05</td>
<td>+/- 0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>low strings</td>
<td>+/- 0.1</td>
<td>+/- 0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>woodwind/brass</td>
<td>+/- 0.2</td>
<td>+/- 0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Riser height and available space do not significantly influence sound exposure. This is because the direct sound of others only changes slightly.

- Screens behind musicians are not effective because they only screen some of the musicians and because reflected sound levels are not affected.

- Hypothetically surrounding screens, that would reduce all other musicians’ direct sound, would influence sound exposure by 1 to 3 dB.

- Reflected sound only significantly influences sound levels at the low strings because the contribution of own and others’ direct sound is relatively low.
Conclusions

• Sound level prediction model for the symphony orchestra is able to predict $L_{A,eq}$ within 2 dB deviation for 65% of the microphone positions taken with a maximum deviation of 6 dB.

• The calculated effectiveness of common control measures to sound exposure of musicians playing in a symphony orchestra is within a limited range of 0.5 to 5 dB and in realistic cases below 2 dB.

• The own instrument’s direct sound has a large contribution to the sound exposure, when playing in the orchestra and even at home.

• It seems that orchestral musicians have no other choice than to protect their ears with ear plugs under all circumstances (individual and group playing) if they wish to avoid the risk of developing hearing damage.
Other solutions?

A screen between you and your instrument

or

More distance between you and your instrument
See you later ?!

Remy Wenmaekers
TU/e, Level Acoustics & Vibration