# Investigations on stage acoustic preferences of solo trumpet players using virtual acoustics

**Sebastià V. Amengual Garí**
Detmold University of Music
amengual@hfm-detmold.de

**Malte Kob**
Detmold University of Music
kob@hfm-detmold.de

**Tapio Lokki**
Aalto University
tapio.lokki@aalto.fi

## ABSTRACT

Acoustical conditions on stage have an influence on the sound and character of a musical performance. Musicians constantly adjust their playing to accommodate to the stage acoustics. The study of acoustical preferences of musicians is part of the characterization of this feedback loop, which impacts on the musicians' comfort as well as on the aural experience of a concert audience.

This paper presents an investigation on preferences of solo musicians on stage. By means of spatial acoustic measurements and real-time auralization, the acoustics of different real rooms are resynthesized in laboratory conditions. Two formal tests are conducted with solo trumpet players: a room preference test and a test investigating the preferred directions of early energy. In the first test, musicians are presented with four different rooms and asked about their preference in five different aspects: practice of instrument technique, practice of concert repertoire, concert performance, ease of performance and sound quality. In the second test the auralized rooms are modified to provide early reflections from different directions (front-back, top-down, sides, no early reflections) and the preference of musicians is investigated.

The results show that the judged aspect or performance context is a key factor in determining the preference of musicians' stage acoustics preference. Drier rooms are preferred for practicing instrumental technique while louder rooms help to reduce the fatigue of the players. Bigger rooms with slightly longer reverberation are preferred for concert piece practice and concert performance. The easiness of performance is proportional to the amount of early energy. Regarding the preference of direction of early reflections, the results suggest that there are no clear differences between preferred directions, and the level of early energy is more important for the comfort of solo musicians on stage.

## 1. INTRODUCTION

Stage acoustic preferences and their impact on musicians have been traditionally studied through two approaches: *in situ* experiments in real rooms or synthesis of room acoustics in laboratory conditions. Lately, the proliferation of room enhancement systems allowed as well the conduction of experiments in hybrid or semi-virtual conditions [1].



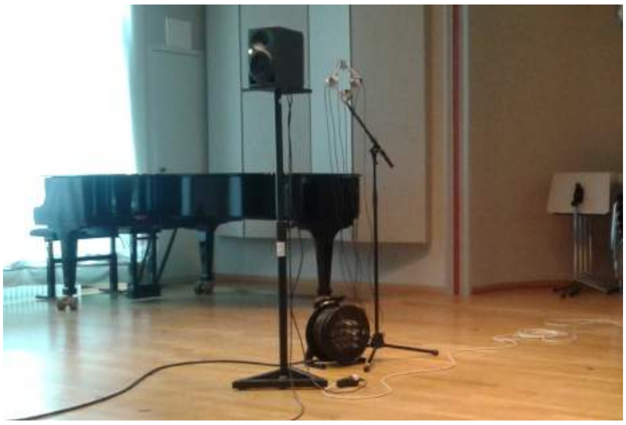

Figure 1: Spatial measurements in Brahmssaal (BS).

The main limitation of laboratory conditions in early experiments was to provide a plausible and realistic acoustic scene using electroacoustic systems. However, given those limitations and the challenge of implementing such virtual environments in real-time, Gade [2] was able to formulate a now widely accepted stage parameter, *stage support* (ST1) from a series of experiments in which a virtual room was generated by mixing the direct sound of a musician with its sound played in a real reverberation room. With the explosion of digital signal processing and increase of computing performance, successive approaches aimed at capturing and reproducing real rooms in laboratory conditions. Ueno *et al.* [3] used a 6-channels system based on directional impulse responses, while a system based on ambisonics reproduction was used by Guthrie *et al.* [4].

This paper uses the real-time auralization system introduced in [5] to conduct experiments on stage acoustics preferences of solo musicians. The auralization method is validated and a method to modify the directional response of an auralized room is proposed. Two experiments are described: a study of room acoustics preference depending on the performance context and a study on the preference of directional early energy.

Figure 2: Validation measurement in the listening environment.

## 2. ROOM AURALIZATION

### 2.1 Measured rooms

Stage spatial measurements were conducted in three rooms of the Detmold University of Music, Germany:

- Brahmssaal (BS): small performance room (approx. 100 seats), regularly used for instrumental lessons and solo performances.
- Detmold Sommertheater (DST): Theater (approx. 320 seats), commonly used for theater, opera and ensemble performances.
- Detmold Konzerthaus (KH): Concert hall (approx. 600 seats) which hosts classical music concerts (ensembles and symphonic music), solo concert examinations and organ recitals.

A measurement set-up composed of a directional studio monitor (Neumann KH120 A) and a microphone array (6 omnidirectional measurement microphones – NTi M2010) is placed on stage at a relative distance of 62 cm, imitating a solo trumpet player situation (Fig. 1 shows the set-up in BS). Spatial Room Impulse Responses (SRIR) are derived and analyzed using the spatial decomposition method (SDM) [6]. An analyzed SRIR consists of an impulse response, in which every sample (pressure value) is associated with a direction (metadata). In auralization the samples of this single impulse response are distributed to all reproduction loudspeakers according to the direction metadata. As the spatial resolution of reproduction loudspeakers is sparse, final mapping of samples to reproduction loudspeakers is done with Vector Base Amplitude Panning [7] (VBAP). Finally, each reproduction loudspeaker has a sparse impulse response, which is convolved in real time with the input signal of a musician. The direct sound is removed from the convolution filters, as it is generated by the instrumentalists. The floor reflection is removed as well, in order to allow the convolution engine to use slightly larger buffer sizes, ensuring the stability of the system. The reproduction of the auralized scenes is achieved using a set-up composed of 13 reproduction loudspeakers in a quasi anechoic room with reverberation times less than 0.1 seconds at mid and high frequencies. Details on the measurements, auralization process, and reproduction set-up are described in [5] and are out of the scope of this paper.

### 2.2 Validation of the auralization

In order to validate the auralization system and compare the acoustic properties of the real and the auralized rooms, spatial measurements were conducted in the virtual environment. The convolution engine was fed with a swept sine signal and measured using the microphone array inside the listening environment (see Fig. 2). The same process as in the real rooms was followed to derive and analyze SRIR of the auralized rooms. Frequency response, auralization error and monaural room parameters (T20, C80) are presented in Fig. 3. Broadband spatiotemporal plots [8] (backward integrated) are presented in Fig. 4. As can be extracted from the measurements, the frequency response of the real and auralized rooms present an error smaller than ± 3 dB in the range of 200 Hz to 5 kHz, approximately. The monaural parameters present a good agreement in the same range, in most cases below the just noticeable difference threshold. The spatiotemporal plots represent the acoustic energy arriving at the player position in the real and auralized rooms, excluding the direct sound and the floor reflection. The analysis show a good agreement in spatial terms, except for room DST, whose auralization presents stronger early reflections from the back side. The increase of diffuse reverberation above 5 kHz can be compensated [9] and a correction routine is provided in the SDM Toolbox [10]. However, the correction procedure was not available when the presented experiments were completed and it will be considered for future experiments. In addition, the overall decrease of brightness is due to non-coherent summation of signals in amplitude panning at high frequencies [11].

### 2.3 Spatiotemporal manipulation

Once the directional information of an impulse response is computed the SRIR can be manipulated to modify the magnitude and directions of specific reflections. In this case, the early reflections of the room are manipulated to modify their energy and directions of arrival. To do that, the rendered impulse responses are split into an early reflections part (subject to spatial manipulation) and an unmodified late reverberation part. A directional weighting function is applied on the early reflections using a time window. The modified impulse response is a combination of modified early reflections and original late reverberation:

$$IR(t,\theta,\phi)_{dir} = IR(t,\theta,\phi)_{ERdir} + IR(t,\theta,\phi)_{LRorig} \quad (1)$$

where $IR(t,\theta,\phi)_{dir}$ is a pressure impulse response with associated directional information and directional weighting of early reflections. $IR(t,\theta,\phi)_{ERdir}$ refers to the early

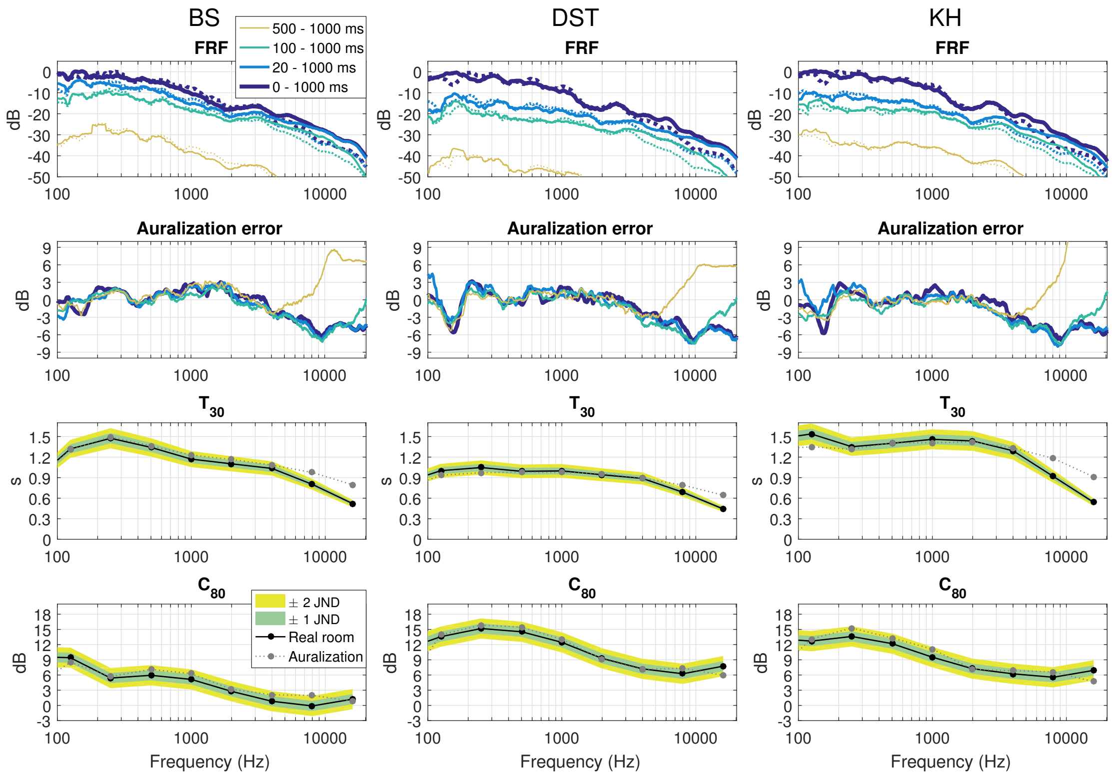


Figure 3: Comparison of frequency response (first row) and auralization error (second row) in different time intervals, and monaural room parameters (third and fourth row) of the measured rooms and their auralizations. Solid and dashed lines on the first row correspond to the real room and the auralization, respectively.

reflections after directional weighting and $IR(t,\theta,\phi)_{LRorig}$ is the late reverberation without modifications.

The two parts of the modified impulse response are:

$$IR(t,\theta,\phi)_{LRorig} = IR(t,\theta,\phi)_{orig} \cdot (1 - w(t)) \quad (2)$$

$$IR(t,\theta,\phi)_{ERdir} = IR(t,\theta,\phi)_{orig} \cdot g(\theta,\phi) \cdot w(t) \quad (3)$$

where $w(t)$ is a time window that defines the limit between early and late reverberation, including a mixing time between them. The term $g(\theta,\phi)$ refers to the spatial weighting function and is based on a cosine weighting in orthogonal directions. Five different cases are defined: all (no modification applied), front-back, sides, top-down, no-ER (early reflections removed completely):

$$g(\theta,\phi) = \begin{cases} 1 & \text{if all} \\ |\cos(\theta)\cdot\cos(\phi)| & \text{if front-back} \\ |\sin(\theta)\cdot\cos(\phi)| & \text{if sides} \\ |\sin(\phi)| & \text{if top-down} \\ 0 & \text{if no-ER} \end{cases} \quad (4)$$

The time window $w(t)$ is defined as

$$w(t) = \begin{cases} 1 & \text{if } t < t_{end} - t_{mix} \\ -1/t_{mix} & \text{if } t_{end} - t_{mix} \leq t \leq t_{end} \\ 0 & \text{if } t > t_{end} \end{cases} \quad (5)$$

where $w(t)$ is the time window, $t_{end}$ is the start of late reverberation and $t_{mix}$ is the mixing time.

## 3. EXPERIMENTS

The goal of the experiments is to explore the stage acoustic preferences of semi-professional trumpet players. To achieve this, two different experiments were carried out:

- General preference: This experiment tries to determine the room acoustical preferences of the players depending on the performance context.
- Directional Early Energy: This experiment examines the influence of the direction of the early reflections on the perceived stage support.

None of the experiments had a time limit, but the duration of every trial was measured for subsequent analysis. There were no requirements regarding the nature of the musical performance, instead, every musician was free to choose what to play in every experiment in order to explore the acoustic feedback of the rooms.

### 3.1 Procedure and aparatus

The experiments consisted on paired comparison tests in which all the stage acoustic conditions were compared against each other. The tests were conducted using a GUI presented on a screen close to the player. The GUI was developed in Max/MSP and was connected to the engine of the virtual environment [5], providing the information of the spatial impulse responses to be convolved in every trial. A trial consisted on the comparison of two rooms and the order of presentation of the trials was randomized. Musicians could switch in real time between the two acoustic

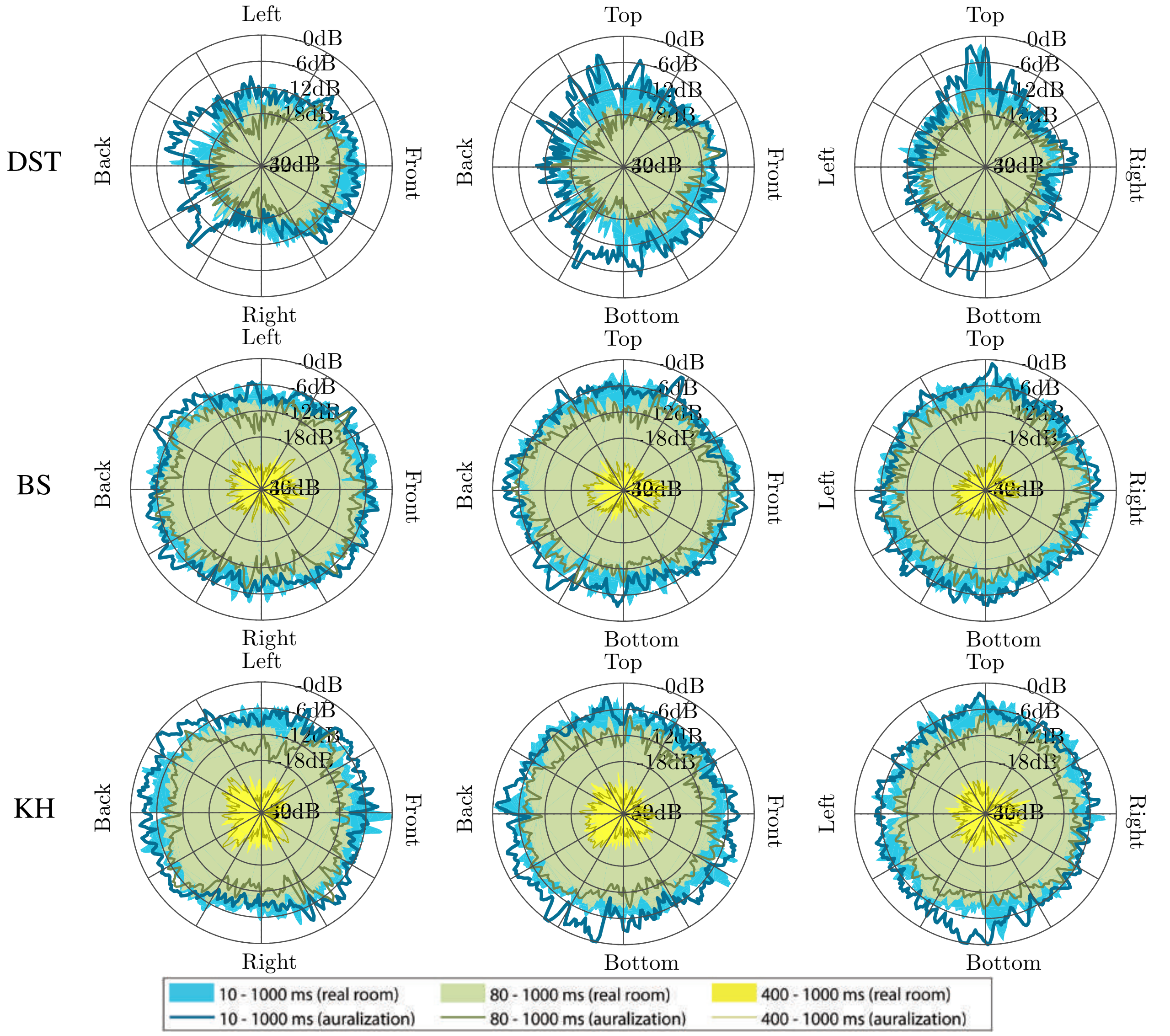


Figure 4: Broadband spatiotemporal representation of the auralized rooms (backward integrated) analyzed at the musician position.

situations and select the preferred choice in every trial by using a MIDI interface. The experimenter was present in the room during the test, but the interaction between the experimenter and the participants was minimized during the experiments to allow freedom in the judgments. An overview of the experimental set-up is presented in Fig. 5. All the participants were students of the Detmold University of Music at bachelor or master level, with an average age of 23 years at the time of the experiment. All of them had previously performed in concerts as soloists or with ensembles in the studied rooms.

### 3.2 General preference

Previous research has investigated musicians' stage acoustics preferences, usually focusing on overall impression or preferred acoustic conditions for concert performance. However, concert performance represents only a small fraction of time compared to the amount of time spent on practice and rehearsal activities. For this reason, five different

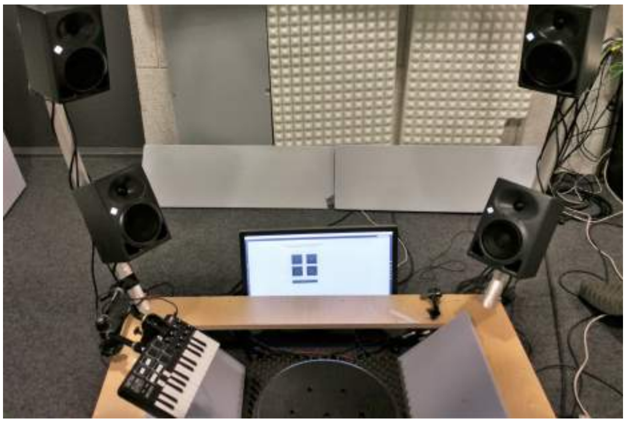

Figure 5: View of the set-up from the musician perspective.

tests are implemented, using the same methodology and acoustic conditions, but investigating five different case scenarios or performance contexts through a different question (in the following order):

- *Practice Technique*: In which room do you prefer to practice instrument technique?
- *Practice Concert*: Which room do you prefer to practice a concert piece?
- *Concert*: Which room do you prefer to perform in a concert?
- *Easiness*: In which room is it easier to perform?
- *Quality*: Which room provides the best overall acoustic (or sound) quality?

The experiment was completed by 7 different players and every section of the test lasted for approximately 10 minutes. The order of the trials was fully randomized, while the order of the test sections was always the same. Depending on the physical and psychological fatigue of the players the tests were completed in one or in two sessions. Five of the players completed a double pairwise comparison (5 tests x 6 pairs x 2 repetitions) with inverted orders to analyze the consistency of their answers. A preliminary analysis revealed a high consistency, thus to reduce the fatigue of the players, the last two players completed only a single pairwise comparison. The responses of these last two players were then duplicated to ensure an equal weight of all subjects in the analysis.

### 3.3 Directional Early Energy

The Early and Late Stage Support parameters provide an estimation for ensemble conditions and perceived reverberation on stage. They calculate the ratio between the direct sound (plus floor reflection), and a correspondent time interval (10 to 100 ms for early support, and 100 to 1000 ms for late support), and are formally defined as follows:

$$ST_{Early} = 10\log\left[\frac{\int_{0.02}^{0.1} p^2(t)dt}{\int_{0}^{0.01} p^2(t)dt}\right][dB] \quad (6)$$

$$ST_{Late} = 10\log\left[\frac{\int_{0.1}^{1000} p^2(t)dt}{\int_{0}^{0.01} p^2(t)dt}\right][dB] \quad (7)$$

where $p$ is the instantaneous pressure of a measured impulse response on stage and $t$ represents time in seconds. According to [2] and the correspondent ISO standard [12], stage parameters must be measured on stage, using an omnidirectional source and a distance of 1 meter between the source and the receiver. However, in the present study the measurement set-up consists of a directive source and a distance between source and receiver of approximately 62 cm. Although this set-up does not comply with the standard measurement requirements, it provides a more realistic approximation of the energy perceived by the musician, taking into consideration the real distance between instrument and performer and the radiation properties of the instrument.

The ability of hearing oneself and other musicians on stage is an important factor to facilitate ensemble performance and previous research suggests that the direction of arrival of early reflections on stage can influence the stage acoustics preferences of chamber orchestras [13], as well as solo musicians [4]. It is not clear, however, how this directionality should be quantified and how it is related to subjective perception of musicians on stage. The goal of the present study is to provide a methodology that allows a systematic study of those preferences in trumpet players using modified versions of the auralized rooms with different early energy levels and directions.

A pilot test was conducted with 5 participants, evaluating their preference in terms of stage support. The term was discussed with the participants to ensure a correct interpretation, and it was agreed that support is related to the ability of hearing their own sound in the room without difficulty or need to force their instrument (as described by Gade [2]).

The experiment followed the same procedure as in the general preference test. In this case there were 3 different rooms with 5 modifications per room (all, front-back, sides, top-down, no-ER). The order of the comparisons was randomized and all the participants rated each pair once, resulting in 30 comparisons (3 rooms x 10 pairs) per participant.

In all the studied halls the starting time of the late reverberation ($t_{end}$) was set to 100 ms, while the mixing time ($t_{mix}$) was 45, 45 and 65 ms for BS, DST and KH, respectively.

### 3.4 Interviews

After the experiments informal interviews were conducted with the musicians, asking them about their preferences, perceived differences between rooms and general opinion about the experiments. It is worth noting that the participants in the presented experiments already participated in previous research experiments [14], thus all of them were familiar with the rooms and their auralized versions. The interviews were based on a cooperative conversation, in an attempt to focus on the aspects that were more important for musicians. A written interview form was provided as well, to provide the opportunity to comment on aspects not present in the conversation.

## 4. RESULTS

The results of the paired comparisons were processed with a Bradley-Terry-Luce (BTL) model, which estimates the probability of preference of every room in each scenario by comparing the result of all the direct comparisons [15]. Tables 1 and 2 show the average and median times per comparison in the tests.

### 4.1 General preference

The estimated preference in every studied case is presented in Fig 6. The results show that the performance context is determinant when choosing a certain kind of stage acoustics over another. Drier rooms are preferred to practice in-

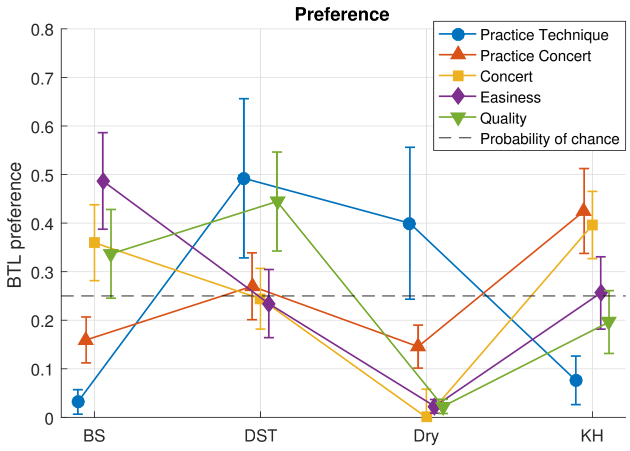


Figure 6: Estimated preference of different rooms depending on the playing purpose.

| | Avg. dur. (s) | Median dur. (s) |
|---|---|---|
| Pract. Technique | 79 | 42 |
| Pract. Concert | 45 | 35 |
| Concert | 33 | 28 |
| Easiness | 41 | 31 |
| Quality | 40 | 31 |

Table 1: Duration of trials for the general preference experiment

| | Avg. dur. (s) | Median dur. (s) |
|---|---|---|
| DST | 38 | 28 |
| BS | 45 | 39 |
| KH | 40 | 27 |

Table 2: Duration of trials for the directional early energy experiment

strument technique, being DST and anechoic conditions the most preferred. The most preferred room to practice a concert (KH) is as well the most preferred room to perform in a concert, and while BS is the second most preferred room to perform in a concert, there is no statistical difference between their preference. The ease of performance is dominated by the loudest room (BS), which together with DST are the best rated rooms in terms of overall sound quality.

In other words, every room stands out in a certain kind of performance context:

- BS: *Concert, Easiness, Quality*.
- DST: *Practice Technique, Quality*.
- Dry: *Practice Technique*.
- KH: *Practice Concert, Concert*.

#### 4.1.1 *Preference and acoustic parameters*

Diverse room acoustic parameters have been extracted from the measured auralizations: reverberation time ($RT_{20}$) and room gain parameters ($G_{all}$, $G_{early}$ and $G_{late}$). The reason for using room gain parameters is that the values of $ST_{early}$ and $ST_{late}$ in anechoic conditions are -∞, thus not allowing curve fitting operations. The parameters are defined as follows:

$$G_{all} = 10 \log \left[ \frac{\int_0^{\infty} p^2(t)dt}{\int_0^{0.01} p^2(t)dt} \right] [dB] \quad (8)$$

$$G_{early} = 10 \log \left[ \frac{\int_0^{0.1} p^2(t)dt}{\int_0^{0.01} p^2(t)dt} \right] [dB] \quad (9)$$

$$G_{late} = 10 \log \left[ \frac{\int_0^{0.01} p^2(t)dt + \int_{0.1}^{\infty} p^2(t)dt}{\int_0^{0.01} p^2(t)dt} \right] [dB] \quad (10)$$

where $p$ is the instantaneous pressure of the impulse response and $t$ is time in seconds. The gain parameters have been computed in frequency bands and averaged over octave bands from 125 Hz to 2000 Hz. The reverberation time is an average of the bands 500 Hz and 1000 Hz.

Considering a previous study that suggested a possible quadratic relationship between early energy and subjective overall impression [16], a quadratic curve fitting has been applied between the room parameters and the average preferences of every case. The fittings are depicted in Fig 7, and only curves with an adjusted $R^2 > 0.6$ are presented. Although the context *Practice Technique* is better suited for drier and quieter rooms, there is no clear fitting between the parameters and the different performance contexts. *Practice concert* presents a quadratic relationship with the late gain of the room ($G_{late}$), while *Concert* presents a quasi linear relationship with $RT_{20}$ and clear quadratic trends with the rest of the parameters. *Easiness* presents a quadratic relationship with $G_{all}$ and seems to benefit from a strong early and overall energy (quasi linear relationship with $G_{early}$ and $G_{all}$ for the studied cases). Finally, *Quality* presents a quadratic relationship with $RT_{20}$.

### 4.2 Directional Early Energy

The BTL estimated preferences regarding the direction of early energy are depicted in Fig. 8. The room DST presents a statistically significant higher preference when all the early energy is present, when compared to any other case. For the rooms BS and KH, although *Front-back* energy is slightly more preferred and *no-ER* is the least preferred case, the differences are not statistically significant.

Comparing the estimated preferences against the $ST_{early}$ values of the modified early energy auralizations it appears that when a certain value of support ($ST_{early}$) is met (from approximately -12 dB and upwards) the amount of early energy or the direction of it are irrelevant (see Fig. 9). This would suggest that the level of the early energy is more important for solo musicians than the direction of arrival of this energy. However, the trends are fairly weak and seem to be room dependent, thus more experiments are needed to draw clear conclusions.

## 5. DISCUSSION

### 5.1 Comments on the results

During interviews, musicians often rated anechoic characteristics (Dry room) to be very difficult to play in, un-

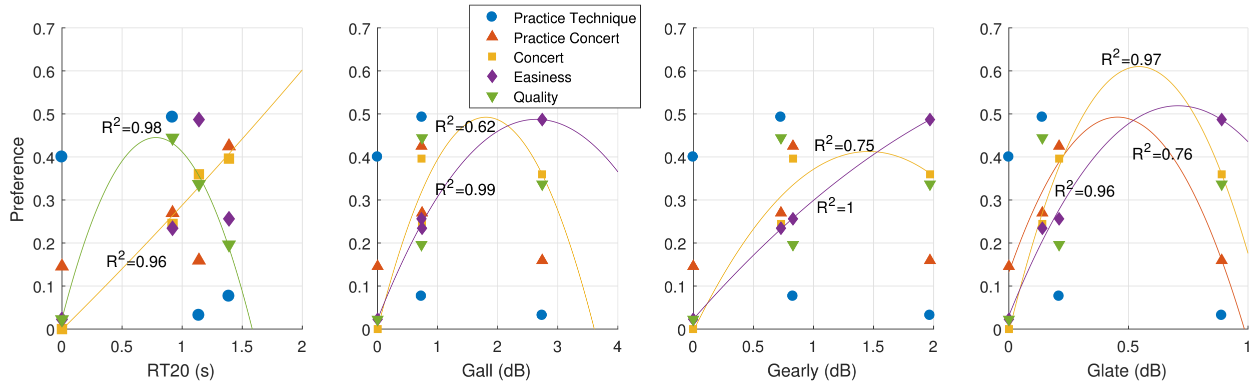


Figure 7: Quadratic fits of the room preferences and room acoustic parameters. The $R^2$ value included in the graph corresponds to the adjusted $R^2$.

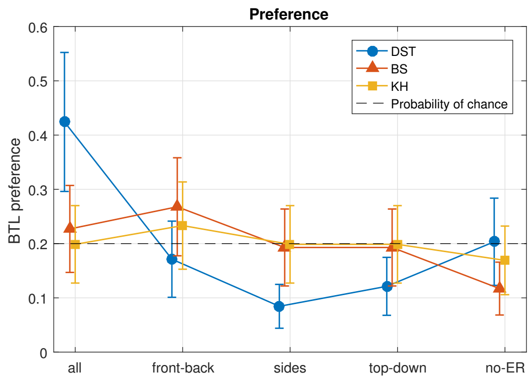


Figure 8: Estimated preference of early energy directions.

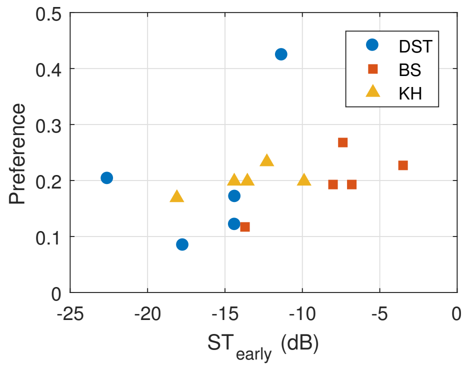


Figure 9: Preference values of directional energy in relation to $ST_{early}$ values.

comfortable and more exhausting. However, in such cases where the playing requires a high level of concentration and ability to hear own mistakes, a very dry room is often preferred. Indeed, a small amount of reverberation is beneficial in keeping a high clarity and reduce the fatigue of the players. When practicing for a concert, the preference shifts towards slightly longer reverberation times and louder rooms, which could be closer to concert conditions. However, it is necessary to retain a certain degree of clarity or early energy, in order allow the detection and correction of musical performance errors or articulation imperfections. When playing in a concert, musicians often prefer longer reverberation times, which could be related with a bigger projection of the instrument and the feeling of playing in front of a bigger audience. The easiness of playing, or musician comfort is directly related with the amount of early energy, as musicians feel more supported by the stage conditions and less effort is needed to develop the notes and feel their presence in the room. During the interviews multiple participants stated that when they feel supported by the room it is easier to relax, reduce fatigue and ultimately perform better. Finally, although in the studied rooms *Quality* seems to be quadratically related with $RT_{20}$, it has to be considered that more aspects, such as tone balance, are involved and purely energetic terms are insufficient to rate the sound quality of a room.

In addition, it is interesting that during the different parts of the first test (general preference), the played excerpts varied substantially depending on the test question. For *Practice Technique* musicians often tended to play fast passages with complex note articulations, meaning that they tended to explore the early response of the room and its clarity. *Practice concert* and *Concert* were usually related with more lyrical passages. However, those technical and lyrical passages could be in many cases parts of the same piece. Additionally, when testing *Easiness* and *Sound Quality* they often played a broad type of pieces with different characters, testing the articulation and judging the tone color and the decay of the rooms. Finally, the trial duration (see Tab. 1) of the *Practice Technique* case is significantly higher than in the other cases ($p < 0.01$), which could indicate that there is a learning effect in judging the different rooms and the task becomes easier when musicians are more familiar with the different conditions.

Regarding the test of directional early energy, most of the musicians commented that in many cases it is very difficult to distinguish which are the differences of the rooms. In fact, most of the players tended to play notes with clear articulation to explore the early part of the sound. As seen in the results, the direction of arrival of the early energy seems to not be relevant to judge their preference, instead the level of the early energy would be more important. It is thus not clear, what would be the directional preference in case of having equal levels in the different cases. In future experiments the effect of the level should be considered in order to include a proper equalization of early energy. In addition, the length of the window and mixing time should be carefully decided to provide a wide and realistic variety of acoustic scenarios. This pilot study demonstrated the potential of manipulating directional energy in virtual environments, allowing a detailed control of the acoustic scene and enabling a systematic study of different stage acoustic phenomena.

### 5.2 Comparability with previous studies

Previous research on stage acoustics for solo musicians usually studied musicians' *preference* of stage acoustics, which intuitively translates to preference to perform in a concert. However, *preference* could be understood as well as sound quality or degree of comfort provided by the room. The present study demonstrates that the same musicians judging the same rooms lead to very different results depending on the formulation of the question and judging criteria or performance context. This makes it very difficult to compare the results of the present study with previous research. However, if we compare the concert conditions with previous results of *preference* the results support former findings. Here, a quasi linear relationship was found between $RT_{20}$ and the preference of a room to perform in a concert and longer reverberation times were also preferred in previous studies (up to 2.3 s [4] and around 1.9 s in [3]). However, the longest (and most preferred) reverberation time in the present test is approximately 1.4 s.

The comparison of stage energy parameters, such as support (ST) or strength (G) depends indeed on the distance between the source and the receiver and the directivity of the source. In addition, while they have been standardly measured in previous research [2, 3], the calibration procedures, instrument directivity and micking techniques applied in the virtual environments leave some room for uncertainties on the absolute values and it is not straightforward to ensure that the same values measured in different virtual environments are equivalent.

## 6. CONCLUSION

Two experiments on musicians' stage preferences are presented. The results demonstrate that the performance context is a key factor for musicians to prefer a particular stage acoustics. Moreover, the direction of the early energy does not seem to play an important role on determining the preference of stage support, while the level of the early energy is more important. The results seem to support partially previous findings, although the comparability of the results depends greatly on the measurement process and calibration process of the virtual environments.

Directions of future work should increase the range of tested rooms and instruments, as well as a careful design of the directional properties of the auralized rooms.

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