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How early reflections affect the stage acoustic conditions for solo musicians

Jannis Kriz [a,b,*], Emanuele Porcinai [a], Steffen Lepa [a], Paula Klein [a], Johannes M. Arend [c,a], Stefan Weinzierl [a]

[a] Audio Communication Group, Technische Universität Berlin, Einsteinufer 17c, Berlin, 10587, Germany
[b] Kahle Acoustics, Avenue Molière 188, Brussels, 1050, Belgium
[c] Acoustics Lab, Department of Information and Communications Engineering, Aalto University, Otakaari 5, Espoo, 02150, Finland

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ABSTRACT

Early reflections are an important factor for the acoustic conditions on stage. To better understand their effect on the perception of musical performers, an experimental study was conducted to investigate how the time and direction of arrival, the diffusivity and the strength of early reflections affect the perceived acoustic quality on stage. Architectural variations of a typical stage structure were created in computer models. Combinations of different stage widths, canopy heights, and surface scattering were modelled using geometric acoustics and Boundary Element Method (BEM) simulations. Listening experiments carried out with musicians of different instrumental groups playing with real-time auralisations of these virtual concert hall stages revealed that both the time and direction of arrival of early reflections have a significant effect on the stage acoustic conditions perceived by solo musicians. In a larger battery of stage acoustic parameters determined for each architectural variation, the 'Top to Sides' and 'Top to Horizontal' ratios (TS, TH) proved to be the best predictors of the acoustic quality of the stage configurations presented, although the interrelation within the musicians seems to be less uniform than for room acoustic parameters from the audience perspective.

1. Introduction

For the perceived acoustic quality of a stage, the balance between early and late incident acoustic energy was identified as an important acoustic factor, leading to the development of established stage acoustic descriptors such as ST_{Early} and ST_{Late} [1]. The time windows used for more recently proposed descriptors such as LQ_{7-40} [2] or G_{7-50} [3, p. 130] are all in a range where reflections are expected to be perceptually fused with the direct sound, thus providing acoustic support to the performing musician.

Other studies, however, have found only weak correlations between a musician's preference and these parameters [3–5]. Instead, these studies found architectural parameters such as the height to width ratio (H/W) of a stage to be more strongly correlated with the perceived overall acoustic impression (OAI) on stage [3]. Thus, both the time of arrival and the direction of early reflections seem to be relevant, rather than only the cumulative energy within a relatively wide time window.

Due to the different design elements of stages, it is challenging to achieve a controlled as well as ecologically valid experimental design, i.e. one that is sufficiently relevant to the "real-world" stage, to investigate their effect on the acoustic conditions in more detail [6, p. 174].

In contrast to studies that have measured soloists' experiences in real spaces with a variety of different stage and auditorium characteristics [7–9], the present study attempts to address this challenge through an experimental investigation, in which solo musicians were invited to perform on virtual stages under laboratory conditions. The structure of a typical stage in an otherwise unchanged concert hall was systematically modified to introduce variations expected to affect the acoustic impression of the stage, such as the distance between musicians and stage boundaries [1,10], the presence of reflectors around the stage (sides+top, sides only, top only) [3,6], and the surface texture of the reflecting surfaces, which has recently been shown to affect echo thresholds within the time range of the precedence effect [11]. These variations were created in computer models and presented to solo musicians via dynamic binaural synthesis. Their acoustic impression was evaluated by means of a questionnaire instrument developed specifically for this target group [12].

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[*] Corresponding author.

E-mail addresses: jannis.kriz@campus.tu-berlin.de (J. Kriz), emanuele.porcinai@tu-berlin.de (E. Porcinai), steffen.lepa@tu-berlin.de (S. Lepa), paula.klein@campus.tu-berlin.de (P. Klein), johannes.arend@aalto.fi (J.M. Arend), stefan.weinzierl@tu-berlin.de (S. Weinzierl).

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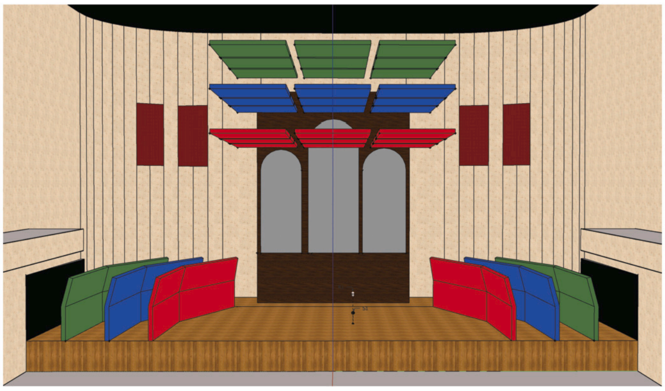

Fig. 1. Overview of stage interventions provided as experimental conditions: Lateral reflective surfaces with a width 16 m (red), 20 m (blue) and 24 m (green), canopies 9.5 m (red), 11.5 m (blue) and 13.5 m (green) high, stage width without interventions 29 m and 16.6 m ceiling height over stage (black).

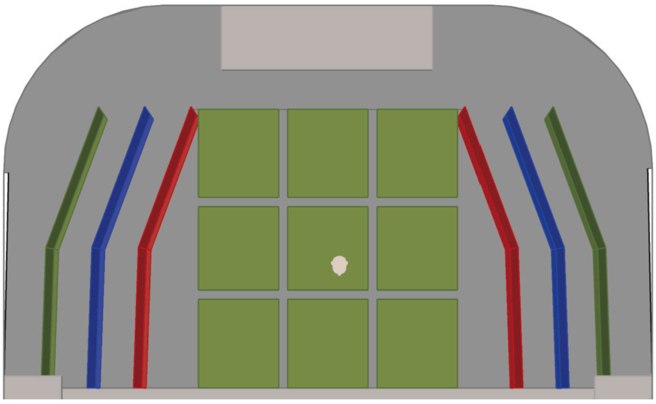

Fig. 2. Top view of the stage interventions: The 9 overhead reflector elements are tilted backwards by 3° and together cover a total width of 12 m and a depth of 11 m with gaps of 0.4 m in between.

2. Methods

2.1. Stage variations and experimental design

The range of typical concert hall stage dimensions, as summarized by Wenmaekers [13, p. 29], provides the framework for the experimental conditions of the present experiment. Variations in time of arrival (TOA) and direction of arrival (DOA) are achieved by three different reflector configurations around the stage: Side reflectors, a canopy alone, or a side reflector plus canopy are added at three different distances (Fig. 1) to an original stage enclosure of an otherwise unaltered concert hall ($V = 19{,}000\ \mathrm{m}^3$, $h = 18$ m, $RT_{30} = 1.9$ s).

The resulting TOA of additional early reflections presented to a solo musician 0.5 m from centre stage in this experiment are 43 ms, 55 ms, 67 ms and 81 ms. For an ensemble it may be reasonable to investigate earlier arrival times as suggested by Marshall (17–35 ms), but for a solo musician at centre stage this would correspond to reflective surfaces that are unrealistically close for a symphonic stage (for example a canopy height as low as 4 m) [14].

The height (3 m) and the structure of the side reflectors (with 11° slanted top edges) are based on a typical stage enclosure design [3, p. 82]. The canopy consists of nine elements, with a total length of 11 m and a total width of 12 m, tilted 3° backwards to avoid a fluttering response (Fig. 2). The size of the gap between the elements is 0.4 m, in order to avoid excessive acoustic separation of the volume above the stage [15].

To investigate the effect of different surface structures, all interventions were performed with two different surface scattering coefficients ($s = 0.1$ vs. $s = 0.85$). Only two scattering conditions were chosen since relevant studies have found that the just noticeable difference in scattering coefficients in concert hall auralizations is of the order of $\Delta s = 0.4$ [16].

The variation of the reflection strength is implicit in all the stage interventions and has been quantified with the parameter $\mathrm{G}_{10\text{–}\mathrm{inf}}$ (total strength at the receiver, without direct sound and floor reflection), which falls within a range between 4.8 dB for the largest stage with only scattering side reflector and 8.8 dB for the smallest stage with reflective sides and canopy.

The final experimental design thus consisted of three statistically independent stage intervention factors (see also Fig. 1): Distance (small, medium, large) x Direction of Arrival (top+sides, sides only, top only) x Scattering of reflectors (reflective, scattering) = 18 conditions for statistical analysis + 1 reference condition without any stage intervention and with medium scattering for comparison.

The participating musicians were selected on the basis of their main instrument, with the aim of forming three subgroups of approximately equal size: strings, brass and woodwinds, thus allowing the analysis of instrument-dependent perceptual differences, the existence of which has been suggested by previous studies [3].

2.2. Binaural room impulse response generation

All stage configurations were modelled in SketchUp®. Binaural impulse responses (BRIR) were then simulated using the RAVEN room acoustic simulation software [17], which proved to be the most powerful in the comparative round robin on room acoustical simulation software [engine E, 18]. Geometric acoustic simulations in one-third octave bands were performed with 300,000 rays and image sources up to order two. The receiver position was located slightly off the stage centre, at 1.5 m height and 5 m distance from the stage edge. Receiver directivity was modelled using head-related transfer functions (HRTF) from the FABIAN database [19]. To account for the expected head movement of the musicians during performance, BRIRs were generated for receiver orientations sampled in 3° steps in the horizontal plane, based on the requirements identified in [20]. The simulation was repeated for each instrument with its respective frequency dependent source directivity, using the OpenDAFF format [21], as well as its respective source position in relation to the performer's body. The geometric simulations use a Lambertian-based scattering model with realistic frequency-dependent values from the relevant literature [22, p. 395].

Since the image source model assumes an infinite boundary size, the frequency-dependent reflection coefficient of the canopy structure was modelled with finite elements up to 1 kHz using the COMSOL® Multiphysics Boundary Element Method (BEM) interface. The scattered response from the BEM model was used to filter the specific image source reflection from the canopy above the musician (see Appendix A). This solution approximates the frequency-dependent effects on timbre caused by a finite canopy taking into account all wave phenomena. By improving the physical accuracy of the simulation, this approach aims to improve the plausibility of the auralisation.

2.3. Auralisation

All stage configurations were auralised using dynamic binaural synthesis, which has previously been shown to produce highly plausible room acoustic simulations [23], also for musical performers [24]. The direct sound of each musician's instrument was captured using a DPA 4099 supercardioid microphone clipped to the instrument (Fig. 3). A Linux instance of the SoundScape Renderer (SSR) was used to convolve the direct sound with the BRIR of the stage configuration under test, for all head rotations, in real time. Head orientation was captured by a Polhemus Patriot® head tracking system. A pair of AKG-K1000 extra-aural

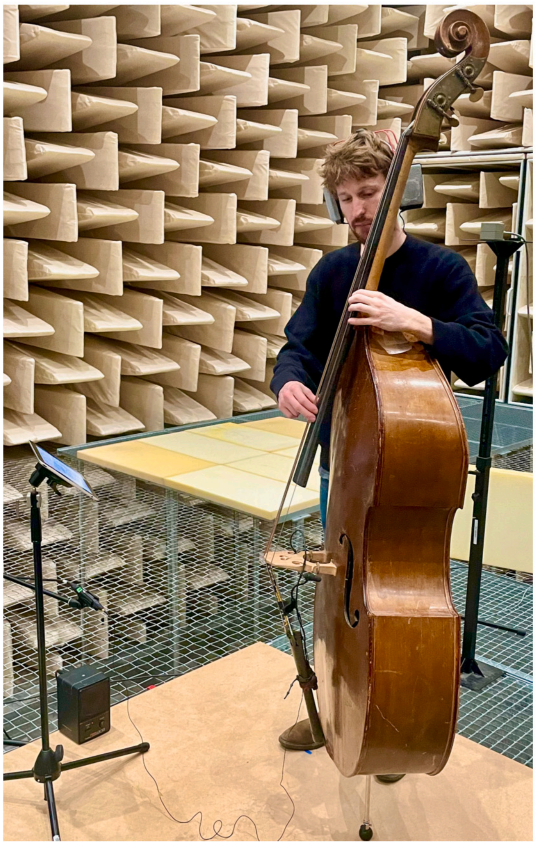

Fig. 3. Musician in the experimental set-up: Extra-aural headphones, head tracker, microphone, tablet, talk-back speaker, wooden floor plate; rendering computer and audio interface located outside the room.

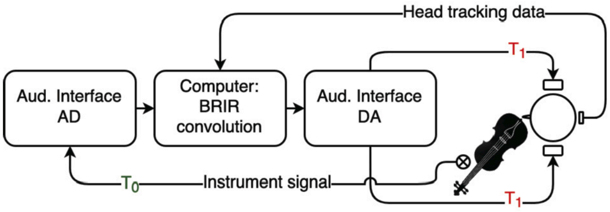

Fig. 4. Auralisation signal flow. Latency compensation between T_0 and T_1.

headphones were used for reproduction, providing near-perfect free-air-equivalent coupling and minimal obstruction of the direct sound to the participant's ears.

The experiment took place in the anechoic chamber of the TU Berlin ($V = 1,850\ \mathrm{m}^3$, $f_c = 63$ Hz). Since the source position in the simulations can only be static, a square rigid wooden plate with a side of 2 m was placed at floor level to create a floor reflection that responds adequately to the movements of the instrument and takes into account the insertion loss due to the presence of the musician's own body. The floor reflection was therefore removed from the simulations by creating a small area of total absorption below the source and receiver positions.

The musicians could hear the direct sound and floor reflection of their own instrument, while the room response was dynamically reproduced through headphones. Fig. 4 shows the signal flow of the auralisation. The global latency of the binaural synthesis system was 32 ms. This is shorter than the earliest time of arrival of the reflections of all stage configurations, and could therefore be eliminated by subtracting the global latency time from all BRIRs.

Table 1
CFA measurement model for perceived stage acoustics of solo-musicians: latent perceptual dimensions and associated items.

Latent factor	Questionnaire item
Quality	Enjoyment (not enjoying–enjoying) Feeling of playing (bad–good) Quality (bad–good acoustics)
Reverberance	Amount of Reverb. (little–a lot) Duration of Reverb. (short–long) Reverberance (dry–reverb.)
Support	Resonance (little–a lot) Projection (carries–does not carry) Room Response (dead–live)
Brightness	Timbre (dull–bright) Tone colour (muff.–rich in overt.)
Room Size	Character (studio like–church like) Room height (low–high) Room size (small–large)

2.4. *Experimental procedure*

A calibration procedure was repeated for each subject in order to provide the correct pressure magnitude of the room response relative to that of the incoming direct sound. Participants were asked to play sustained notes on their instrument. These were recorded with both the instrument microphone and a dummy head (Neumann KU 81) placed 5 m away from the musician. The same distance and binaural receiver was used in an anechoic environment simulation, with the same source level as that used to simulate the BRIRs in the concert hall environment, to produce a free-field reference BRIR. This was then convolved with the previously recorded sustained test signal from the musician and played back through the headphones on the dummy head. The RMS level difference between the two dummy head measurements would determine a gain factor for the stage BRIRs in the experiment. The calibration was repeated for each participant as it depends on the exact position of the microphone in relation to the instrument (see schematic in Appendix B, Fig. B.12).

18 performers with an average age of 29 years (SD = 10.9) and an average of 15 years of concert experience (SD = 9) participated in the experiment. Six of them were string players (two violins, one viola, two cellos, one double bass), seven were woodwind players (two clarinets, one flute, one recorder, one bass clarinet, one tenor saxophone, one soprano saxophone) and five were brass players (one trumpet, one French horn, one Vienna horn, one trombone, one tuba). To avoid any bias, the instructions given to the performers did not include any information about the purpose of the study. In order to familiarise the participants with the setup and to provide them with an anchor for perceiving the variety of stimuli, two very different stage configurations from the entire sample of stage conditions to be tested were presented for training. For the experiment, musicians were asked to play the same excerpt of their choice for one minute in each of the 19 virtual stage configurations (see Appendix D, Table D.6). After each configuration presented, participants were asked to complete the questionnaire (see above Table 1) presented on a tablet. To reduce the potential impact of order effects, the order of presentation of the stages was randomised once for half of the musicians and reversed for the other half. A session lasted approximately two hours and could be interrupted by a short break if the participant so wished.

2.5. *Perceptual assessment*

For perceptual assessment, we adapted a preliminary version of the Stage Acoustic Quality Inventory (STAQI) [12] for the current study, omitting items related to ensemble playing. This assessment framework provides a more detailed insight into the perceptual qualities of different stage acoustic conditions than single ratings of the Overall Acoustic Impression (OAI), as mostly used in previous studies. The constituting items are the result of an elicitation process from 65 attributes describing stage acoustic conditions taking into account the specific vocabulary of musicians. The elicited attributes are the result of a confirmatory factor analysis (CFA) that explain maximum portions of perceptual variance in the collected datasets of the above cited study. The resulting questionnaire consisted of 15 items, to be rated from 1–100, measuring the latent perceptual dimensions *Quality*, *Reverberance*, *Support*, *Brightness* and *Room Size*. Table 1 provides an overview of the questionnaire items and associated latent perceptual dimensions.

2.6. Statistical analysis

In a first step, the effect of all varied properties of the auralised stage configurations, i.e., the position, distance and surface texture of the introduced reflectors, on the five factors of the perceived stage acoustic qualities was analysed by estimating the factor scores for each trial of each participant using the CFA model described in section 2.5 and averaging the factor scores over each group of measurements of interest. The reference stage with no reflector interventions around the stage was included in this part of the analysis.

In a second step, we used structural equation modelling (SEM) to test for significant effects of the 18 simulated combinations of stage acoustic interventions and their manipulated temporal-spatial patterns of early reflections on all five perceptual dimensions. The reference stage, with no reflector interventions around the stage, was not included in this part of the analysis. SEM is a statistical modelling approach that allows multiple relationships between variables to be examined in a single model. In the present case, it was used as an advanced multivariate statistical technique in order to (1) address the challenge of relatively small expected effect sizes in the face of expected large measurement errors, (2) clearly separate the effect of stage acoustic interventions on perceived *Quality* from effects on other perceptual dimensions, and (3) estimate the unique causal effects of TOA, DOA and scattering independently of the unique causal effects of *Strength*, since they are all confounded when stage acoustic interventions are performed.

As exogenous predictor variables, the SEM we estimated (Fig. 10) uses two dummy variables for each of the three levels of the experimental factors TOA and DOA, one dummy variable for each of the two levels of the factor *Diffuseness*, and *Strength* as a metric covariate. The dependent endogenous variables are the five correlated latent factors of our CFA measurement model (see Table 1).

All statistical analyses were carried out using R with the Jamovi graphical user interface extended by the SEMLj package [25]. SEM and CFA estimates were obtained using a standard maximum likelihood (ML) estimator and a 5% level of significance. Factor loadings in CFA and path coefficients in SEM were z-standardised for better interpretability. Standard errors of the estimates were corrected with a Huber-White sandwich estimator to account for the 18 within-subject measurements.

2.7. Stage-acoustic parameters and perceptual impression

In addition to the established stage acoustic parameters $\mathrm{ST}_{\mathrm{Early}}$ and $\mathrm{ST}_{\mathrm{Late}}$ [1,3–5], several alternative parameters have recently been proposed. The newly proposed parameters use alternative time windows of integration and relative distance corrections as well as, more recently, directional energy ratios. These can be obtained by measuring the impulse responses with Ambisonics microphones, and their relevance seems plausible when one considers, for example, that the ratio of the height to width of a stage is a significant factor in the perceived overall quality of a stage [6,26]. A collection of these newly suggested parameters that can be applied to solo musicians on stages was calculated for each of the 18 stage variations simulated in this study (Table 2).

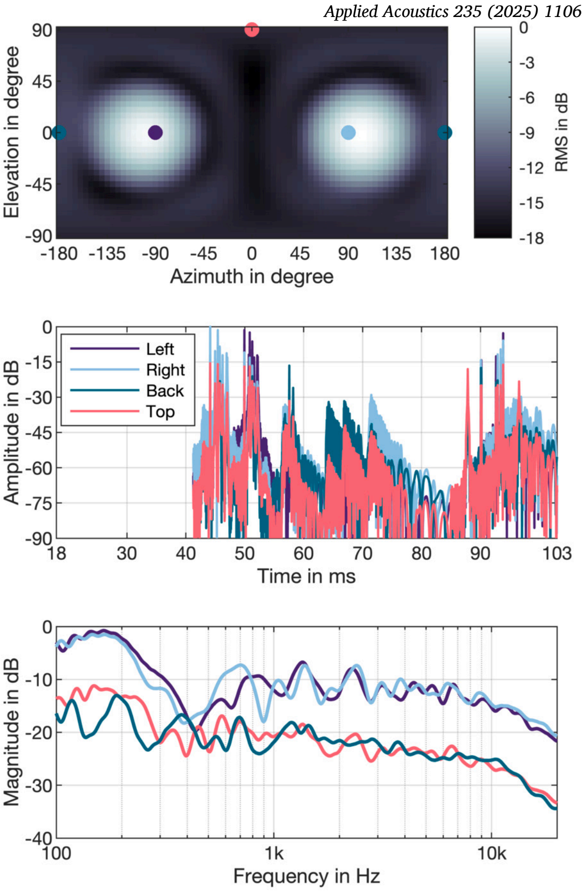

Fig. 5. Top: Normalised RMS level in dB over space of an ARIR in the time interval from 15 to 100 ms after the arrival of the direct sound. The coloured markers indicate the four steering directions (purple - left, blue - right, teal - back, pink - top). Middle: Result of the beamforming, i.e., directional impulse responses for the four directions in the corresponding time interval. Bottom: Magnitude spectra of the four directional impulse responses.

The calculation of these directional parameters is analogous to that of many other established room acoustic parameters when they are monaural. In the case of the directional parameters, we used the Ambisonics room impulse responses (ARIRs) simulated with the RAVEN geometrical acoustics software. Simulations were performed analogously to an $\mathrm{ST}_{\mathrm{Early}}$ conform measurement, with the source and receiver at 1.5 m height, one meter apart, both facing the audience. Similar to [26,6], we applied beamforming with a spatial order of $N = 2$ to estimate the energy coming from the four directions left, right, back, and top, where the directions Ω were defined by azimuth ϕ and elevation θ, with $\Omega_{\mathrm{L}} = (-90°, 0°)$ for left, $\Omega_{\mathrm{R}} = (90°, 0°)$ for right, $\Omega_{\mathrm{B}} = (180°, 0°)$ for back, and $\Omega_{\mathrm{T}} = (0°, 90°)$ for top. Steering in these directions was performed using spherical harmonic domain beamformers with modal weighting to achieve a hypercardioid beam pattern (i.e., normalised plane wave decomposition with maximum directivity beamformers) [27, Ch. 4], [28, Ch. 5], [29, Ch. 6]. The resulting four directional impulse responses were then used to determine the directional stage acoustic parameters shown in Table 2.

Fig. 5 further illustrates the described processing with an example. The upper plot shows the energy over space of an ARIR in the time interval from 15 to 100 ms after the arrival of the direct sound (according to TS_{100} and TH_{100} estimation, cf. Table 2), clearly showing strong lateral reflections. The coloured markers indicate the four steering directions. The plots below show the result of the beamforming, i.e., the directional impulse responses for the four directions (middle) and their corresponding magnitude spectra (bottom). The plots indicate energy differences

Table 2
Established and newly proposed parameters to characterize room acoustical conditions for musicians on stage.

Monaural	
ST_{Early}	Levels of early reflections (20–100 ms) relative to the direct sound at a distance of one meter from the source, averaged from 250 Hz to 2 kHz [1]
ST_{Late}	Levels of late reflections (100 ms–inf) relative to the direct sound at a distance of one meter from the source, averaged from 250 Hz to 2 kHz [1]
CS	Clarity on stage, averaged from 250 Hz to 4 kHz [5]
EMDT	'Early-Mid-Decay-Time'; EDT within 20–130 ms, a time interval supposed to be supportive for musicians on stage, averaged from 1 to 2 kHz [30]
RR160	'Running Reverberation' as perceived reverberation during a musical performance, averaged from 500 Hz to 2 kHz [31], [3]
LQ_{7-40}	Evaluating very early reflections against later energy without direct sound; meant to be descriptive for cross stage communication, averaged from 500 Hz to 2 kHz [2], [3]
G_{7-inf}	Strength without direct sound on stage with 10 m reference, averaged from 500 Hz to 2 kHz [32], [3]
G_{7-50}	Strength without direct sound on stage within 7–50 ms with 10 m reference, averaged from 500 Hz to 2 kHz [32], [3]
G_{Early}	Early strength on stage within 0–80 ms with 10 m reference, averaged from 500 Hz to 2 kHz [32], [3]
G_{Late}	Late strength on stage 80 ms–inf with 10 m reference, averaged from 500 Hz to 2 kHz [32], [3]
Directional	
LF	Ratio between energy coming from sides in time interval 5–80 ms and energy coming omnidirectionally in time interval 0–80 ms, averaged from 1 to 2 kHz [33], [3]
$LQ_{7-40,TS}$	Spatial ratio of LQ_{7-40} parameter measured with multi-channel spherical transducer with spatial analysis of incoming reflections, a variant proposes ratio of top/sides [6], [26]
$EDT_{Top/Back}$	Spatial ratio of EDT based on multi-channel measurement [6]
$RR160_{Back}$	Spatial version of RR160 based on multi-channel measurement [6]
$ST_{Early,Top/Sides}$	Spatial ratio top to sides of ST_{Early} based on multi-channel measurement [6]
TS	'Top to Sides' ratio within 15–50 or 15–100 ms, respectively, measured with a spherical transducer, averaged from 250 Hz to 2 kHz [26]
TH	'Top to Horizontal' ratio within 15–50 or 15–100 ms, respectively, measured on directional, averaged from 250 Hz to 2 kHz [26]
DD	'Directional Diffusion' as the ratio of sum of energies incoming to a spherical array and anechoic response [6]
Architectural	
H/W	Ratio of stage height and width [3]

between left/right and back/top, with higher energy for the sides, resulting in negative values for TS_{100} and TH_{100} in this example.

In order to test to what extent these parameters can predict listeners' perceptual impressions of the simulated stages, we estimated z-standardised factor scores for all latent variables of the CFA model documented in Table 1 using the regression method of SEMLj and then calculated bivariate Pearson correlations with all stage acoustic parameters.

3. Results

3.1. Playing on virtual stages

The participating musicians reported that the simulated acoustic environments that were presented to them sounded plausible and natural. The extra-aural headphones, which allowed them to hear the direct sound of their instrument undisturbed, were reported not to interfere with their playing. Some reported that some of the rooms reminded them of halls they had already played in before. After the experiment, many of the participants were surprised to learn that only the stage had been varied in the environments presented, while the hall had remained virtually unchanged. This confirmed that the stage acoustic interventions produced clearly audible differences.

As intended by leaving the choice of the pieces up to the musicians, the music played in the experiment had a wide range in terms of acoustic signal properties such as tempo, dynamics, density, tone colour, etc (see Appendix D).

One aspect that was repeatedly mentioned by the musicians after the experiment was that the suitability of a room acoustic environment always depends largely on the piece being played. At the same time, some room acoustic properties can only be perceived if the content being played has certain characteristics in terms of dynamics, articulation and timbre. Thus, the choice of music influenced not only the musician's sensitivity to the magnitude of changes in the room acoustics, but also his or her evaluation of them. The number of 19 acoustic environments presented proved to be at the upper limit for the musicians in terms of fatigue.

Table 3
CFA measurement model for perceived stage acoustics of solo-musicians (factor inter-correlations allowed) including McDonald's ω and average variance extracted (AVE) per factor. Overall model fit: SRMR=0.03, RMSEA=0.071, CFI=0.974; χ^2=210, df=80, p<0.001.

Latent factor	Questionnaire item	β
Quality	Enjoyment (not enjoying–enjoying)	0.95
ω=0.96	Feeling of playing (bad–good)	0.95
AVE=0.86	Quality (bad–good acoustics)	0.86
Reverberance	Amount of Reverb. (little–a lot)	0.90
ω=0.91	Duration of Reverb. (short–long)	0.84
AVE=0.77	Reverberance (dry–reverb.)	0.90
Support	Resonance (little–a lot)	0.92
ω=0.93	Projection (carries–does not carry)	0.88
AVE=0.82	Room Response (dead–live)	0.91
Brightness	Timbre (dull–bright)	0.82
ω=0.87	Tone colour (muff.–rich in overt.)	0.93
AVE=0.76		
Room Size	Character (studio like–church like)	0.86
ω=0.87	Room height (low–high)	0.81
AVE=0.69	Room size (small–large)	0.82

3.2. Perceptual assessment model fit

Table 3 provides an overview of the resulting measurement model, including the item loadings that were derived by confirmatory factor analysis (CFA) of the questionnaire responses in the present study, as well as the overall CFA model fit, the reliability (ω) and efficiency (AVE) coefficients for each factor. The data shows a strong model fit that confirms the perceptual latent dimensions and items that have been elicited for the STAQI framework [12].

3.3. Descriptive analysis

As the results in Fig. 6 show, the perceived *Quality* decreased as the distance of the side and top reflectors from the playing position in the

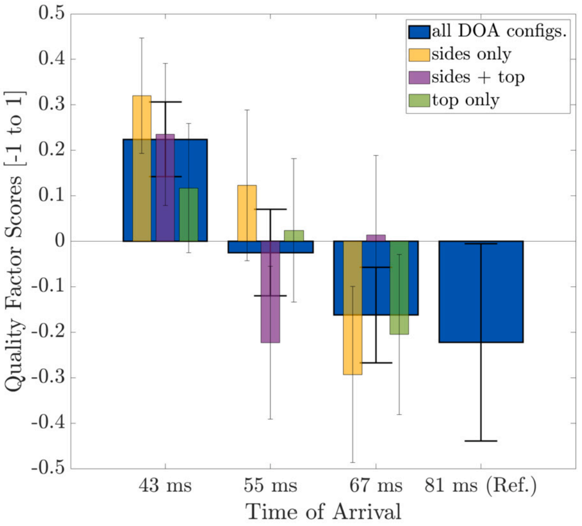

Fig. 6. Perceived stage acoustical *Quality* (blue) by time of arrival and reflector configurations (the reference stage has no additional reflectors); means and standard errors.

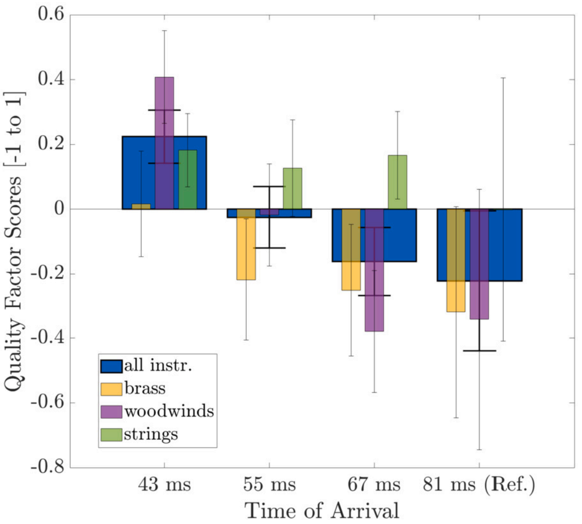

Fig. 7. Perceived stage acoustical *Quality* by time of arrival and instrumental groups, showing a preference for the earliest tested times of arrival for woodwinds and brass instruments; means and standard errors.

centre of the stage, associated with larger TOAs and less *Strength*, increased. The reference stage with no additional reflectors inside the hall had the lowest mean *Quality* rating. For reflections with TOA up to 55 ms, there was a tendency to prefer a side reflector only over a top reflector only or a combination of the two. For medium tested arrival times (55 ms), the configuration with top and side reflection was disliked, while this was the preferred setting for the reflectors placed the furthest away.

A comparison of the *Quality* impressions of members of different instrumental groups (Fig. 7) shows that the perceived differences obtained were most pronounced for woodwind players, followed by brass players, while string players were hardly affected in their *Quality* impressions by the stage acoustic interventions we made. The marked preference of woodwind players for shorter TOA seems to be mainly due to the increased *Brilliance* provided by reflective surfaces closer to the instrument (Fig. 8). In contrast, string players' perception of brilliance was only affected for the latest arrival times tested, but does not seem to be related to the perceived quality of these late reflections (see Fig. 7).

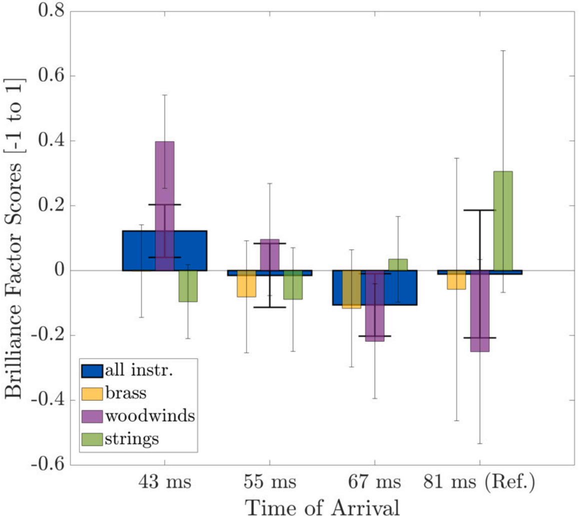

Fig. 8. Perceived *Brilliance* of the stage acoustic conditions by time of arrival and instrumental groups: woodwinds are most sensitive for perceived brilliance, with higher perceived brilliance the earlier the reflection. String instruments perceive increased brilliance only for the latest tested reflections; means and standard errors.

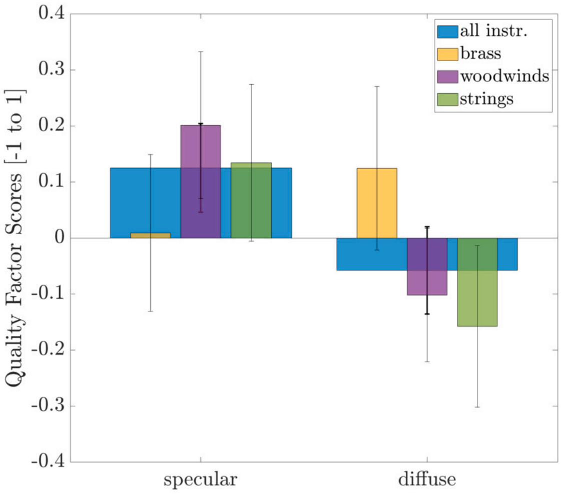

Fig. 9. Perceived stage acoustical *Quality* by reflector scattering property and instrument group: preference trend for woodwinds and strings for specular early reflections, brass instruments prefer diffuse reflections; means and standard errors.

Fig. 9 reveals a subtle trend in perceived *Quality* favouring specular reflectors over diffusing reflectors across all tested configurations. Evaluating the results per instrument group, it can be observed that woodwinds and strings generally preferred the specular early reflections, while they disliked diffuse reflections. Contrary, the brass instruments were preferring diffusing early reflections.

3.4. Effects of architectural interventions on stage acoustical impressions

Fig. 10 shows the results of the SEM estimation we performed in order to test for causal influences of early reflection qualities on different dimensions of stage acoustic impressions. In particular, we found a significant positive effect of short TOAs (43 ms) on perceived *Quality*, compared to stages with longer TOAs ($p<0.029$, $\beta=0.13$). Short arrival times also significantly increased the perceived *Brilliance* compared to the medium and large TOAs ($p<0.025$, $\beta=0.18$). Beyond the TOA, neither *Strength*, nor any other reflection quality had a statistically significant effect on perceived *Quality*. The absence of a side reflec-

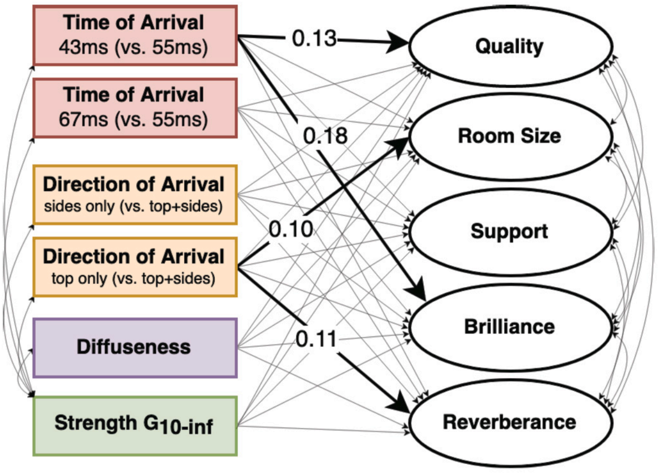

Fig. 10. Structural equation model (SEM) testing the unique contribution of individual reflection qualities to the stage acoustic perception of solo musicians. Significant paths are shown as bold arrows, including standardised β regression coefficients. Model fit: SRMR=0.025, RMSEA=0.037, CFI=0.97; χ^2=267, df=140, p<0.001.

tor, however, resulted in a significant increase in perceived *Room Size* ($p<0.026$, $\beta=0.10$) and *Reverberance* ($p<0.04$, $\beta=0.11$).

Interestingly, *Strength* $G_{10\text{–inf}}$ had no statistically significant effect on *Quality* or any of the other factors. This means that any unique effects of *Strength* on stage acoustic qualities must have been smaller than the effects of TOA resulting from the same intervention, i.e., varying the distance of the reflectors from the centre of the stage. Moreover, the trends observed in the descriptive analysis regarding the reflector's scattering properties are not sufficiently pronounced to achieve statistical significance under the two-sided hypothesis testing within the SEM framework.

3.5. Relevance of stage acoustics parameters

As a second approach, an attempt was made to predict the five perceptual factors using the battery of established and newly proposed room acoustic parameters (Table 2). Table 4 shows the bivariate correlations with the factor scores of the five latent perceptual impression factors obtained from the participant's data. Included are all stage acoustic parameters applicable to solo musicians, calculated from the reference condition and the 18 stage variations simulated in this study. The results show small but significant correlations between some monaural parameters and perceived *Quality*: *Clarity on Stage* (CS) and *Early-Mid-Decay-Time* (EMDT) are negatively correlated with *Quality*, while two *Strength* parameters ($G_{7\text{–}50}$, G_{Late}) are positively correlated. For some parameters, however, the variation generated by the architectural interventions performed was relatively small, e.g. for G_{Early} with values between 20.1 and 20.2 dB. This indicates that certain parameters do not capture the architectural interventions made, but at the same time the changes made do not allow conclusions to be drawn about the relevance of these parameters.

For the directional parameters, we found highly significant negative correlations between perceived *Quality* and the TS-, and TH-parameters calculated in the 15–50 ms time interval. This confirms the preference for early lateral energy over early top energy also seen in the SEM for ceiling vs. lateral reflectors, and is consistent with the results found for chamber music ensembles by [26]. In contrast to previous findings for orchestral stages [3], the height to width ratio (H/W) applied to the distances to the reflector panels, was not a significant predictor of *Quality* in our study.

Regarding the significance values in Table 4, it should be noted that we did not analyse specific hypotheses for individual parameters. In this respect, the bivariate correlation matrix can be interpreted as a multiple test of a global null hypothesis (there is no correlation between the 23 parameters and the quality of the stages), the significance level of which would have to be corrected for alpha error accumulation, e.g., using the Holm-Bonferroni method [34]. As none of the correlations would then be significant, we interpret the correlations, especially those of the 'Top to Sides' and 'Top to Horizontal' measures, as a strong trend to be confirmed by future studies.

4. Discussion

The current study presents an experimental approach to investigate the effect of different stage configurations on the perception of performing musicians. The influence of early reflections, as they are often generated by added reflectors to the side and above the stage, was simulated using a combination of BEM models and ray tracing, and auralised by dynamic binaural synthesis of the room response. By systematically varying the stage architecture and thus the acoustic properties of its early reflections without changing the rest of the hall, the specific effects of the time and direction of arrival as well as the diffuseness of the reflectors could be analysed. A quality inventory for the perceptual assessment of room acoustics by musicians (STAQI) was adapted for soloists and showed a good fit to the collected data.

A significant main effect on the perceived stage acoustic *Quality* was found for the TOA of the additional reflectors created, with a preference for the earliest TOA (43 ms) compared to medium (55 ms) and large TOAs (67 ms). This is consistent with Gade's finding that reflections as late as 50 ms no longer contribute to the acoustic support of one's own instrument [1]. In this respect, the time window of the recently proposed stage parameter $G_{7\text{–}50}$ [3, p. 130] seems suitable also for solo musicians.

The fact that early reflection TOA has a significant positive effect on perceived *Quality*, while no such effect was found for $G_{10\text{–inf}}$, suggests that – at least for a solo musician – a favourable temporal structure of early reflection seems to be more important than the magnitude resulting from its integration: A louder stage is not necessarily perceived as more supportive. Note that the statistical estimation used allowed to separate the unique effects of both quantities.

The best rating of the overall stage *Quality* was found for early side reflections only, with no canopy present. The tendency to prefer early side reflections to early top reflections confirms previous studies which have found that orchestra musicians prefer high and narrow stages to low and wide stages [3]. The musicians' tendency to prefer *only* side reflectors for the smaller stage configurations may indicate that, where useful early reflections coming from the sides are present, unobstructed or later feedback from the hall volume overhead is preferred.

A greater distance of reflecting surfaces from the playing position in the centre of the stage leads to a lower *Quality* of the acoustic conditions for solo musicians. The preference of earlier reflections is most pronounced for woodwinds, less so for brass, while the acoustic perception of strings seems to depend least of all on the exact arrival time of the reflections, even if the presence of early reflections is generally just as positively connoted as with the other instrument groups. While increasing TOA is also accompanied by a degradation of the perceived *Brilliance* of the sound of their own instrument for woodwinds, the opposite is true for strings.

The reasons for this instrument-specific behaviour may lie in the nature of the sounds produced, where the less transient sound (slower onset and decay times) in the typical envelope of string instruments may tend to fuse the early reflections more easily and over a longer time window with the direct sound. The instrument-specific role of bone-conducted sound in masking and fusing of early reflections may also play a role and may be an interesting topic for future research.

For an improved understanding of the instrument-specific interaction with added reflectors, it may be interesting to know the sound energy fraction that is radiated by the different instruments towards the varied reflectors. We have therefore calculated this fraction by weighting the solid angle of the varied reflectors with the respective instrument

Table 4

Bivariate correlations between the stage acoustical parameters (Table 2) and the measured perceptual factors, with p-values in brackets. The parameters have been calculated in octave bands. Where not explicitly stated in Table 2, an frequency averaging was performed over the range from 500 to 2000 Hz. The units of the minimum and maximum values are in dB, except for EMDT (s), $EDT_{Top/Back}$ (s), DD (%) and H/W (unitless).

Parameter	Reference	Min; Max	Reverberation	Support	Quality	Timbre	Size
Monaural							
ST_{Early}	[1]	-20.60; -13.00	-0.048 (.376)	0.006 (.908)	0.096 (.077)	-0.030 (.583)	-0.015 (.788)
ST_{Late}	[1]	-20.30; -18.70	-0.063 (.243)	-0.045 (.411)	0.029 (.588)	-0.046 (.399)	-0.037 (.495)
CS	[5]	15.10; 18.20	0.013 (.813)	-0.047 (.389)	-0.121 **(.026)***	0.006 (.915)	-0.034 (.533)
EMDT	[30]	1.62; 2.04	0.051 (.345)	-0.008 (.884)	-0.111**(.039)***	0.030 (.584)	0.012 (.819)
RR160	[31], [3]	-21.90; -21.00	0.022 (.689)	-0.017 (.751)	-0.068 (.210)	0.012 (.830)	0.016 (.770)
LQ_{7-40}	[2], [3]	-12.20; -0.70	0.072 (.183)	0.021 (.701)	-0.095 (.079)	0.024 (.654)	0.031 (.563)
G_{7-inf}	[32], [3]	7.85; 9.74	-0.042 (.439)	0.012 (.828)	0.097 (.073)	-0.038 (.486)	-0.001 (.978)
G_{7-50}	[32], [3]	6.64; 8.22	0.005 (.923)	0.061 (.261)	0.115 **(.034)***	-0.003 (.954)	0.037 (.496)
G_{Early}	[32], [3]	20.10; 20.20	-0.050 (.353)	-0.014 (.794)	0.058 (.281)	-0.053 (.328)	-0.025 (.640)
G_{Late}	[32], [3]	-0.16; 2.87	-0.020 (.711)	0.036 (.505)	0.109 **(.045)***	-0.016 (.764)	0.027 (.618)
Directional							
LF	[33], [3]	-10.40; -2.48	-0.063 (.246)	-0.009 (.846)	0.101 (.063)	-0.012 (.823)	-0.025 (.639)
$LQ_{7-40,Top}$	[6]	10.40; 12.60	-0.014 (.803)	-0.069 (.204)	-0.069 (.206)	-0.011 (.839)	-0.031 (.567)
$LQ_{7-40,Sides}$	[6]	8.23; 14.10	0.007 (.904)	-0.040 (.462)	-0.093 (.085)	-0.011 (.844)	-0.041 (.455)
$LQ_{7-40,Top/Sides}$	[26]	0.79; 1.32	-0.008 (.887)	0.024 (.656)	0.076 (.161)	0.007 (.898)	0.035 (.522)
$RR160_{Back}$	[6]	16.70; 19.00	0.021 (.696)	0.002 (.976)	-0.051 (.345)	0.050 (.359)	0.000 (.993)
$ST_{Early,Top/Sides}$	[6]	0.79; 1.32	-0.008 (.887)	0.024 (.656)	0.076 (.161)	0.007 (.898)	0.035 (.522)
TS_{50}	[26]	-17.10; -6.48	0.025 (.641)	-0.040 (.462)	-0.145 **(.007)****	-0.024 (.663)	-0.003 (.960)
TH_{50}	[26]	-16.20; -10.50	0.012 (.826)	-0.055 (.313)	-0.148 **(.006)****	-0.025 (.641)	-0.012 (.819)
TS_{100}	[26]	-17.20; -1.02	0.075 (.164)	0.043 (.430)	-0.079 (.146)	0.009 (.872)	0.040 (.463)
TH_{100}	[26]	-16.80; -4.42	0.072 (.184)	0.040 (.456)	-0.080 (.141)	0.010 (.852)	0.037 (.500)
DD	[6]	1.43; 2.86	-0.045 (.406)	0.009 (.874)	0.100 (.066)	-0.039 (.477)	-0.005 (.920)
Architectural							
H/W	[3]	0.33; 1.00	-0.018 (.739)	0.011 (.845)	0.075 (.168)	0.004 (.935)	-0.014 (.797)

* $p < .05$, ** $p < .01$

directivities as used in simulation of the BRIRs for one example of each instrument group (see Appendix C, Table C.5). The results show that the violins with their overall less directional sound radiation at medium and high frequencies radiate a greater proportion of energy to the reflectors than a clarinet or trumpet. Although this does not directly correspond to the energy received back by the musicians, it can be seen as an indicator of the strength of the interaction with the particular reflector configuration. However, this does do not explain why the strings were less sensitive to the variations provided.

In terms of the diffuseness of the added reflectors, woodwinds and strings tended to favour specular over diffuse early reflections, while brass instruments preferred more diffuse reflections. Although scattering models in geometric acoustics do not fully capture all the physical effects of diffusion, this observation corresponds well with the authors' experience in stage acoustics, where brass instruments often prefer some diffusion, presumably 'taking the edge off' from early reflections. For the other instrument groups, the preservation of the temporal envelope, which has been shown to be relevant for the audience [35], may also play an important role on stage, depending on the instrument played. The effects of diffusion, however, may be different in an ensemble configuration: Firstly, uniformity of energy distribution across the stage may play a more important role [22]. Secondly, strong diffusion may disrupt the coherence of perceived acoustic cues from reflections with their physical origin, which may be important for meaningful musical communication within an ensemble.

For the present study, a larger set of stage acoustic parameters has been implemented, including the two support parameters ST_{Early} and ST_{Late} mentioned in ISO 3382-1 [36] and 21 other room acoustic parameters, 12 of which are intended to characterize not only the temporal structure but also the direction of incidence of early sound reflections [6]. Of all the calculated parameters, the 'Top to Sides' (TS) and 'Top to Horizontal' (TH) ratios correlate most strongly with the perceived *Quality* in the present study, again indicating a preference for horizontal over top energy within the first 50 ms. The proposal of these parameters [26] was motivated by the previously found relevance of the stage height to width ratio (H/W) [3]. Although they point in the same direction, the signal-based directional parameters have been shown to be better predictors of perceived stage quality than H/W, both in the original study for a chamber ensemble [26] and in our study for solo musicians.

The proximity of the additional reflectors to the centre of the stage, which was positively correlated with the perceived quality in our experiment, seems to be better represented in the bivariate correlation matrix by strength measures such as G_{7-50} than by clarity measures such as CS or LQ_{7-40}, which determine the energy ratio between early and late energy. This ratio even decreases for the smaller stages in our stage configurations, due to higher order reflections increasing the energy retained on the smaller stages also beyond the early time window. In this respect, it seems questionable whether clarity measures such as CS, especially with a large 'early' time window of 80 ms, are suitable as descriptors of perceived stage acoustic conditions.

The positive effect of G_{late} on perceived quality confirms previous studies [3,37] showing the importance of an audible response from the hall back to the musicians in the later time window. G_{late} is monoaural and cannot quantify the direction from which the later response arrives and is perceived. As for the spatial parameters of the early sound field, it may be a subject for future studies to investigate the effect of anisotropy also in the late sound field. The negative effect of EMDT (EDT within 20–130 ms) also confirms earlier findings that stages with lower EMDT are preferred [30].

The magnitude of the correlations between the stage acoustic parameters and the perceived qualities of the different stage acoustic conditions is nevertheless small for the whole battery of calculated parameters. We suspect that there are two reasons for this:

On the one hand, the logic of room acoustic parameters from the audience perspective, such as the early lateral energy fraction, where a fixed time window and a cosine weighting of the direction of incidence provide a good predictor of the perceived width of the sound source, may not be transferable to sound sources in the immediate vicinity. The available results rather indicate that the arrival time of early reflections itself plays a role and should possibly be included in the calculation as a metric variable, rather than including or excluding its effect by means of a fixed window. In the same manner suitable parameters describing the balance between the early and the late sound field on stage should be considered.

On the other hand, the effects of room acoustics from the perspective of the musicians seem to be less uniform than from the perspective of the audience, and depend much more on the instrument used and the piece played [24]. This was explicitly emphasized by many of the musicians after the experimental session (cf. section 3.1). It may therefore be difficult to find room acoustic parameters at all that allow a reliable characterisation of the acoustic conditions on stage, independent of the instruments, the size of the ensemble and the repertoire.

However, one effect seems to be evident across all instrument groups: early reflections are important. For soloists in the centre of a large stage, these reflections can only be achieved with additional reflective surfaces. They increase the perceived brilliance of the own sound and the perceived overall quality of the acoustics. For soloists, they should ideally occur within the first 50 ms, corresponding to a maximum distance to the reflectors of approximately 8 m, and they should preferably come from a lateral direction of incidence, especially at shorter distances.

Future research investigating the effects of stage architectural variation on ensemble playing in a similar methodological framework will show whether the observed effects, such as a preference for early side reflections, are also confirmed in an ensemble situation where ‘hearing others’ becomes as important as the ‘hearing oneself’ situation examined in the current study.

5. Conclusions

An experimental study was conducted to investigate the effect of early sound reflections on solo performers as influenced by the stage acoustic design and additional reflectors on the sides and above the stage. Architectural variations of a typical stage structure, including different stage widths, canopy heights and surface scattering, were simulated using a combination of geometric acoustics and the boundary element method (BEM), and listening experiments were conducted with musicians of different instrumental groups playing with real-time auralisations of these virtual stages. The results show that both the time and direction of arrival of early reflections have a significant effect on the stage acoustic conditions perceived, with a significant preference for reflectors providing a time of arrival (TOA) earlier than 50 ms relative to the direct sound, and a tendency to prefer only side reflections at these early TOAs. This preference was strongest for woodwind and brass instruments, and less so for strings. Within a larger set of stage acoustic parameters determined for each architectural variation, the ‘Top to Sides’ and ‘Top to Horizontal’ ratios (TS, TH) proved to be highly significant predictors of the acoustic quality of the stage configurations presented, again confirming the preference for lateral over top reflections. However, the relationship between these room acoustic parameters and the perceptual qualities of the stage appears to be less consistent with respect to the instruments and the music performed, and thus less strong than that for room acoustic parameters from the audience’s perspective.

CRediT authorship contribution statement

Jannis Kriz: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Emanuele Porcinai:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Steffen Lepa:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Paula Klein:** Writing – review & editing, Validation, Software, Investigation. **Johannes M. Arend:** Writing – review & editing, Visualization, Validation, Software. **Stefan Weinzierl:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Stefan Weinzierl, Emanuele Porcinai reports financial support was provided by Deutsche Forschungsgemeinschaft. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Simulated ceiling reflector response

To improve the physical and perceptual accuracy of the acoustic simulation, the frequency response of the finite and patched canopy reflector was calculated using the 3D boundary element method (BEM). The canopy image source in the ray-tracing model was then filtered using this response. This was done up to about 1 kHz, where most diffraction effects are expected for audible frequencies. Fig. A.11 shows the BEM result for the patched canopy compared to a continuous canopy of similar overall size. As expected, the response of the patched reflector is more irregular, with a pronounced dip at 80–100 Hz and a boost at 300–600 Hz, probably due to the superposition of the edge effects of the individual patches of the reflector. This modulation may result in audible colouration, while the differences in the bass response may only be relevant for the double basses in the context of self-hearing on stage. For flat continuous reflectors, it should be noted that an analytical approximation of the finite reflector response based on the Fresnel zones gives good results compared to the BEM solution (see Fig. A.11), obviously in a fraction of the computational time ([38]).

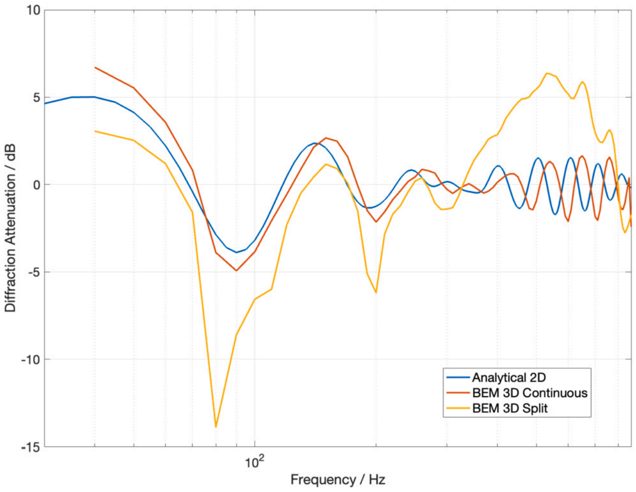
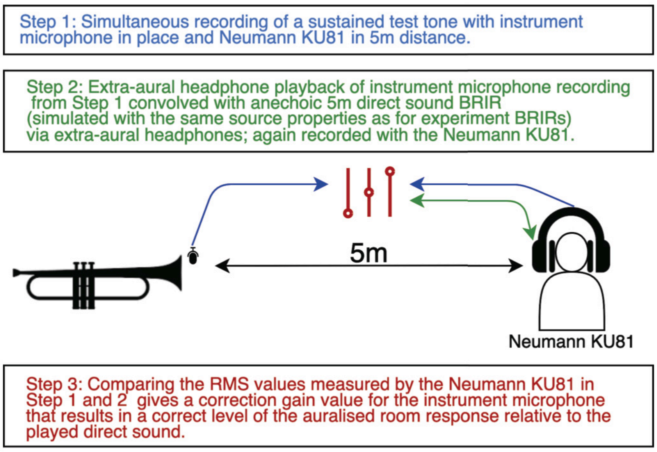


Fig. A.11. Reflector frequency responses (11 m x 12 m): ‘Analytical 2D’ refers to a continuous canopy modelled with 2D assumption in two directions with analytic approximation ([38]). ‘BEM 3D Continuous’ refers to this continuous canopy modelled with BEM, while ‘BEM 3D Split’ refers to the same canopy but patched in a grid with gaps modelled with BEM, see Fig. 2.

Appendix B. Direct to auralisation level calibration procedure


Step 1: Simultaneous recording of a sustained test tone with instrument microphone in place and Neumann KU81 in 5m distance.

Step 2: Extra-aural headphone playback of instrument microphone recording from Step 1 convolved with anechoic 5m direct sound BRIR (simulated with the same source properties as for experiment BRIRs) via extra-aural headphones; again recorded with the Neumann KU81.

Step 3: Comparing the RMS values measured by the Neumann KU81 in Step 1 and 2 gives a correction gain value for the instrument microphone that results in a correct level of the auralised room response relative to the played direct sound.

Fig. B.12. Schematic describing the level calibration procedure that was applied for each participant: the correct playback level of the auralised room responses via the headphones relative to the natural direct sound of the musicians.

Appendix C. Incident sound energy fraction on varied reflectors per instrument

Table C.5
Range of energy ratio - emitted to reflected - calculated as a percentage, for one selected instrument from each instrument group: violin, clarinet and trumpet. The highest values correspond to the closest configurations of the reflectors, the lowest values to the most distant. All values are energetically averaged over the frequency range 500 - 2000 Hz and correspond to the direct sound energy emitted in this frequency range towards the various reflectors in the acoustic ray tracing simulation. Not all of this energy is actually received back by the musician, but the values are considered to be an instrument-specific measure of the interaction strength with the tested reflector variations.

Instrument	Sound energy to side reflector	Sound energy to canopy	Cumulated top + sides
Violin	left: 2.5–5.5% right: 1.9–4.2%	6.3–14.7%	10.7–24.4%
Clarinet	left: 1.5–3.4% right: 1.7–4.0%	5.3–12.9%	8.5–20.3%
Trumpet	left: 1.4–3.2% right: 1.3–3.1%	4.1–10.0%	6.8–16.3%

Appendix D. Music played in the experiment

Table D.6
Title or description of the music played in the experiment by the different instrumentalists.

Instrument	Played music
Clarinet	J. Stamitz - Clarinet concerto in B-flat major, 1st movement - Allegro moderato
Trumpet	J. Haydn - Trumpet concerto in E-flat major (Hob. VIIe:1), 1st movement - Allegro
Violoncello	J. Haydn - Cello concerto no. 2 (Hob. VIIb:2), 1st movement - Allegro moderato
Violoncello	J. S. Bach - Cello Suite No. 3 (BWV 1009), Prelude - Presto
Flute	C. Debussy - Syrinx (L. 129) - Un peu mouvementé - au Movement, très modéré
Tenor saxophone	Quick bebop improvisation
Clarinet	C. Della Giacoma - Tosca-Fantasy (op. 171) - Andante lento
Vienna horn	M. Lewis - How High the Moon (jazz standard)
Violin	J. S. Bach - Partita No. 2 (BWV 1004), Sarabande - Adagio
Double bass	L. v. Beethoven - Symphony No. 9 (op. 125), IV. Finale - Presto
Soprano saxophone	J. S. Bach - Aria from Goldberg variations (BWV 988) - Andante
Tuba	C. Saint-Saëns - Songs without Words (arr. Walter Hilgers), I. Aimons-nous - Assez lent
Violin	M. Ravel - Tzigane - Lento, quasi cadenza
Viola	B. Bartók - Viola Concerto (Sz. 120), 1st movement - Moderato
Bass clarinet	Improvised solo passages
French horn	Romantic, orchestral solo passage
Recorder	J. van Eyck - Questa dolce Sirena from Der Fluyten Lust-Hof, part II - Allegro
Trombone	J. Sandström - Sång til Lotta - Andante

Data availability

Data will be made available on request.

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