DOI: 10.61782/fa.2023.0113

forumacusticum 2023

EFFECT OF EARLY REFLECTIONS ON STAGE ACOUSTIC CONDITIONS FOR SOLO MUSICIANS

Jannis Kriz[1*] **Emanuele Porcinai**[1] **Steffen Lepa**[1] **Stefan Weinzierl**[1]

[1] Audio Communication Group, Technische Universität Berlin, Germany

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 carried out to examine how the time and direction of arrival, the diffusivity and the strength of early reflections affect the perceived acoustical quality on stage. Architectural variations to a typical stage structure were created in computer models. Combinations of different stage widths, canopy heights and surface scattering were modeled 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.

Keywords: *Early Reflection, Stage Acoustics, Perception, Solo Musician*

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, which led to the development of established stage acoustic descriptors such as ST_{early} and ST_{late} [1]. The time windows applied to these as well as to more recently proposed descriptors such as $LQ_{7\text{–}40\text{ms}}$ [2] or $G_{7\text{–}50\text{ms}}$ [3, p. 130] are all in a range where reflections are expected to be perceptually fused with the direct sound, thus providing acoustical support for the performing musician.

Other studies, however, have found only poor correlations between a musician's preference and these parameters [3–5]. Instead, these studies found architectural parameters such as the height over 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 to investigate their effect on the acoustic conditions in more detail [6, p. 174]. The present experimental study attempts to address this challenge through an investigation, in which solo musicians were invited to play 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 acoustical impression of the stage, such as the distance between musicians and stage boundaries [1, 7], 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 [8]. 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 [9].

**Corresponding author*: *jannis.kriz@campus.tu-berlin.de.*
Copyright: *©2023 Kriz, J. et al. This is an open-access article distributed under the terms of the Creative Commons Attribution 3.0 Unported License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.*

2. METHODS

2.1 Choice of stage variations

The range of typical dimensions of concert hall stages as summarized by Wenmaekers [10, p. 29] provides the framework for the experimental conditions of the present experiment. Variations of time of arrival (TOA) and direction of arrival (DOA) are achieved by three different reflector configurations around the stage: Side enclosures, a canopy alone, or a side enclosure plus canopy are added at three different distances (Fig. 1) to an original stage enclosure of an otherwise unaltered concert hall ($V = 19,000\,\mathrm{m}^3$, $h = 18\,\mathrm{m}$, $RT_{30} = 1.9\,\mathrm{s}$). The resulting TOA of additional early reflections presented to a solo musician 0.5 m off center 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 (17–35ms), but for a solo musician at center 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) [11].

The height (3 m) and structure of the side enclosure walls (with angled top) is 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. 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 [12].

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 the just noticeable difference found for concert hall auralisations was quite high, with $\Delta s = 0.4$ [13].

The variation of the reflection strength is implicit in all stage interventions and was quantified with the parameter $G_{10ms\text{–}inf}$ (total strength at the receiver, without direct sound and floor reflection), with values between 4.8 dB (largest stage with only scattering side reflector) and 8.8 dB (smallest stage with reflective sides and canopy).

The final experimental design thus consisted of three statistically independent stage intervention factors (see also figure 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.

Participants were selected on the basis of their main instrument, with the aim of forming three sub-groups 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].

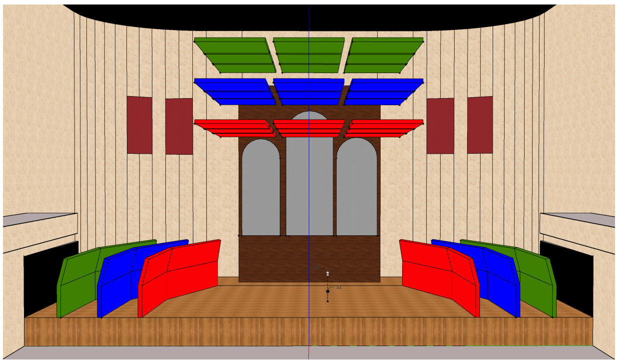

Figure 1. Overview of stage interventions provided as experimental conditions: Lateral reflective surfaces with a width 16 m (red), 20 m (blue) and 24 m (green), canopies at 9.5 m (red), 11.5 m (blue) and 13.5 m (green) height, stage width without interventions 29 m and 16.6 m ceiling height over stage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

2.2 Binaural Room Impulse Response generation

All stage configurations were modelled in SketchUp®. Binaural impulse responses (BRIR) were then simulated with the RAVEN room acoustical simulation software [14]. 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 center, 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 [15]. To account for the expected head movement of the musicians during performiance, BRIRs were generated for receiver orientations sampled in steps of 3° in the horizontal plane. The simulation was repeated for each instrument with its respective frequency dependent source directivity, using the OpenDAFF format [16], as well as its respective position with respect to the performer's body. The geometric simulations use a Lambertian-based scattering model with realistic frequency-dependent values from the relevant literature [17, 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. This solution allows the frequency-dependent effects on timbre caused by a scattering canopy to be approximated using finite element reflectors.

2.3 Auralisation

All stage configurations were auralised using dynamic binaural synthesis, which has previously been shown to produce highly plausible room acoustic simulations [18], also for musical performers [19]. The direct sound of each musician's instrument was captured using a DPA 4099 supercardioid microphone clipped to the instrument (Fig. 2). A Linux instance of the Sound Scape 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-1000 extra-aural 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 ($V = 1,850\,\mathrm{m}^3$, $f_\mathrm{c} = 63\,\mathrm{Hz}$). 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 as well as taking 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. Figure 3 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 reflections of all stage configurations, and could therefore be eliminated by subtracting the global latency time from all BRIRs.

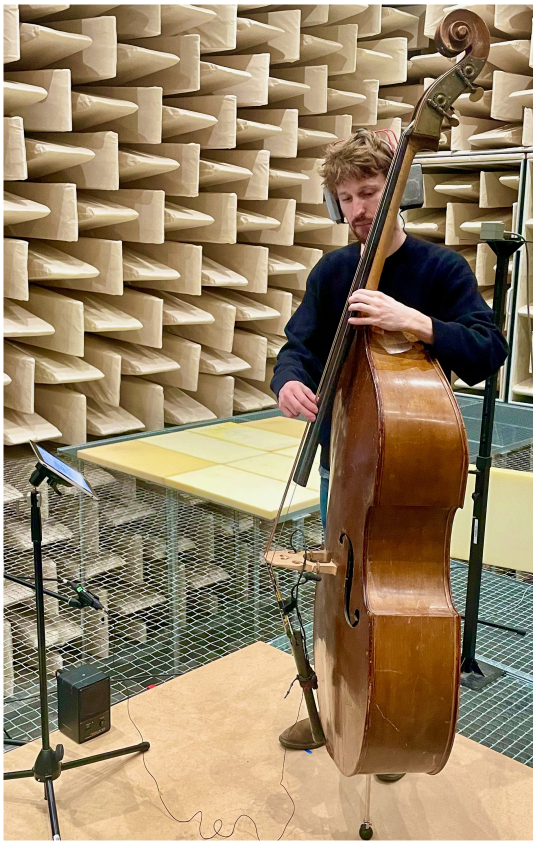

Figure 2. Musician in the experimental set-up: Extra-aural headphones, head tracker, microphone, tablet, talk-back speaker, wooden floor plate; rendering computer and audio interface located outside the room

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 tones on their instrument. These were recorded with both the instrument microphone and a binaural dummy head (Neumann KU 81i) placed 5 m away from the musician. The same distance and binaural receiver were 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 and played back through headphones on the dummy

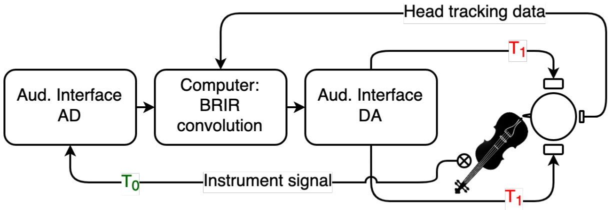

Figure 3. Auralisation signal flow. Latency compensation between T_0 and T_1

head. The RMS level difference between the two dummy head measurements would determine a gain factor for the stage BRIRs. The calibration was repeated for each participant as it depends on the exact position of the microphone in relation to the instrument.

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 woodwinds players (two clarinets, one flute, one recorder, one bass clarinet, two tenor saxophones, 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 instruction given to the performers did not include any information about the aim 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 sample of presented conditions 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. After each presented configuration, participants were asked to complete the questionnaire (see below) 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) [9] for the current study, omitting items related to ensemble playing. This instrument 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 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 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 and the reliability (ω) and efficiency (AVE) coefficients for each factor.

Table 1. 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

2.6 Statistical Analysis

In a first step, the effect of all varied properties of the auralised stage configurations, i.e., position, distance and surface texture of the introduced reflectors on the five factors of the perceived stage acoustical 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 without 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 acoustical interventions and the temporal-spatial patterns of early reflections manipulated by them on all five perceptual dimensions. The reference stage with no reflector interventions around the stage was not included in this part of the analysis. A SEM is a statistical modeling approach that allows to examine multiple relationships between variables at the same time in one 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 acoustical intervention effects on perceived *Quality* from effects on other perceptual dimensions, and (3) estimate the unique causal effects of TOA, DOA and Scattering independently from the unique causal effects of *Strength*, since all of them are confounded when performing stage acoustical interventions.

As exogenous predictor variables, the SEM we estimated (Fig. 7) 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 [20] extended by the SEMLj package [21]. 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-standardized for better interpretability. Standard errors of estimates were corrected with a Huber-White sandwich estimator to account for the 18 within-subject measurements.

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 to not interfere with their playing. Some reported that several rooms reminded them of halls they had already played in. 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.

In the absence of any visual cues, the variation in the stage architecture alone significantly altered their acoustic perception of the room. It seems likely that the choice of musical piece influenced the musician's sensitivity to the magnitude of the changes in room acoustics. The number of 19 acoustic environments presented was considered reasonable, but at the upper limit in terms of fatigue.

3.2 Descriptive analysis

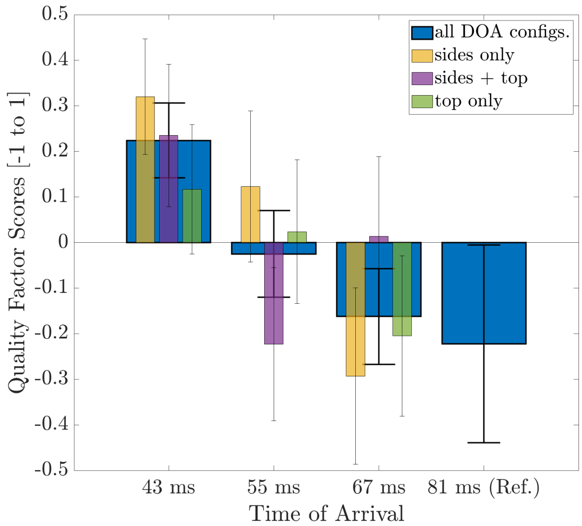

Figure 4. Perceived stage acoustical *Quality* (blue) by time of arrival and reflector configurations (note: the reference stage has no additional reflectors); means and standard errors

As the results in Figure 4 show, the perceived *Quality* decreased as the distance of the side and top reflectors from the center of the stage increased, probably due to larger TOAs and less *Strength* at the same time. The reference stage with no additional reflectors inside the hall had the lowest mean *Quality* rating. For TOAs 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.

A comparison of the *Quality* impressions of members of different instrumental groups (Figure 5) shows that the 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 appears to be due to the increased *Brilliance* provided by reflective surfaces closer to the instrument (Figure 6.

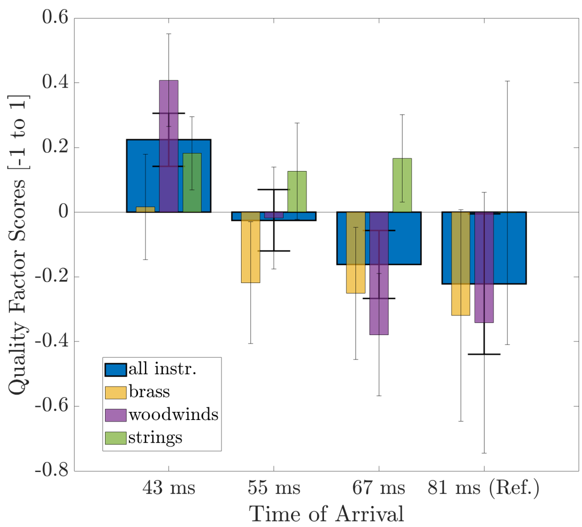

Figure 5. Perceived stage acoustical *Quality* by time of arrival and instrumental groups; means and standard errors

3.3 Effects of architectural interventions on stage acoustical impressions

Figure 7 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 very small TOAs (43 ms) on perceived *Quality*, compared to stages with larger TOAs ($p<0.029$, $\beta=0.13$). At the same time, very short arrival times also significantly increased the perceived *Brightness* 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 reflector, however, resulted in a significant increase in perceived *Room Size* ($p<0.026$, $\beta=0.10$) and *Reverberance* ($p<0.04$, $\beta=0.11$).

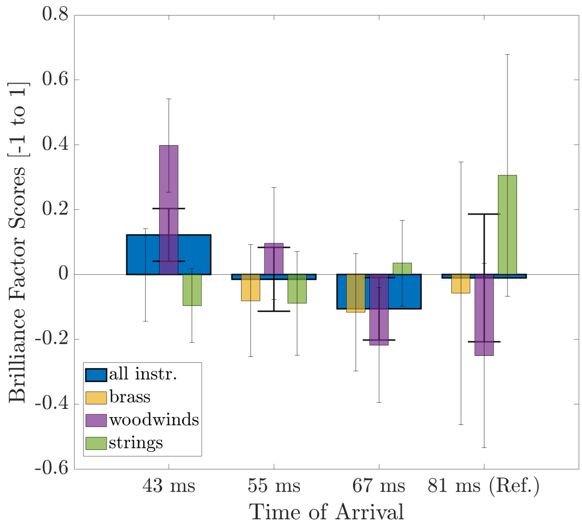

Figure 6. Perceived *Brilliance* of the stage acoustic conditions by time of arrival and instrumental groups; means and standard errors

Interestingly, *Strength* $G_{10ms-inf}$ had no statistically significant effect on *Quality* or any of the other factors. This means that any unique effects of *Strength* on stage acoustical 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 center of the stage. Furthermore, neither type of scattering of the simulated reflectors had a significant influence on stage acoustic impression we measured.

4. DISCUSSION AND CONCLUSION

Based on the results presented, it can be concluded that the framework of the present study provides useful and significant insights into how musicians on stage perceive the acoustic qualities of early reflections. Stage environments have been successfully auralised in real time, integrating the canopy scattering response calculated with BEM models. This framework allowed the investigation of the largely multi-dimensional nature of this scenario by systematically varying the stage architecture - and thus the acoustic properties of its early reflections - without changing the rest of the hall and without any visual cues. The perceptual measurement model, based on the preliminary STAQI questionnaire [9], was adapted for a solo musician

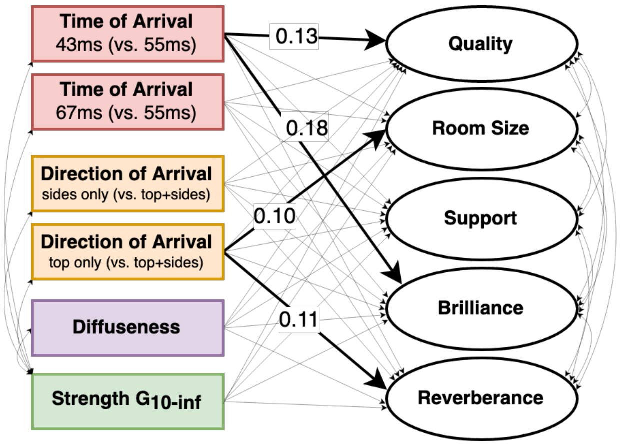

Figure 7. Structural equation model (SEM) testing the unique contribution of single reflection qualities on stage acoustic perception of solo musicians. Significant paths are displayed as bold arrows including standardized β regression coefficients. Model fit: SRMR=0.025, RMSEA=0.037, CFI=0.97; χ^2=267, df=140, p<0.001.

and showed a good fit to the sampled data.

A significant main effect on the perceived stage acoustic *Quality* was found for the TOA of the additional reflectors created, with a significant 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 windows of integration of recently proposed stage parameters such as $LQ_{7\text{–}40ms}$ [2] and $G_{7\text{–}50ms}$ [3, p. 130] seem justified for solo musicians.

The fact that early reflection TOA has a significant positive effect on perceived *Quality*, while no such effect was found for $G_{10ms\text{–}inf}$, 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. 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. The observed preference for later reflections from the top rather than the sides is consistent with findings from case studies in real halls, where raising the canopy often provided a subjective improvement for the musicians [22].

A greater distance of reflecting surfaces from the centre of the stage leads to a lower *Quality* of the acoustic conditions for solo musicians, which is accompanied by a degradation of the perceived *Brilliance* of the sound of their own instrument. This tendency is most pronounced for woodwinds, less so for brass, while the acoustic conditions for strings are hardly affected.

The relevance of the DOA of early reflections, not only for the perceived *Quality*, but also for the perceived *Room Size* and *Reverberance*, suggests that it should be taken into account by non-monaural descriptors of stage conditions such the recently proposed [6].

No significant effect of the scattering properties and the resulting diffuseness of the reflected sound was found for solo musicians. This may be different in an ensemble configuration, where the uniformity of energy distribution across the stage may play a more important role [17].

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. ACKNOWLEDGMENTS

The current study was supported by DFG Grant WE 4057/9-2. The authors would like to thank Dr. Eckhard Kahle for his valuable advice on the topic.

6. REFERENCES

[1] A. C. Gade, "Investigations of musicians' room acoustic conditions in concert halls. ii: Field experiments and synthesis of results," *Acustica*, vol. 69, pp. 249–262, 1989.

[2] E. W. van den Braak, "New (stage) parameter for con-

ductor's acoustics? - part 2: further investigation on LQ7-40," in *Internoise*, (Ottawa, Canada), 2009.

[3] J. Dammerud, *Stage acoustics for symphony orchestras in concert halls*. PhD Thesis, University of Bath, 2009.

[4] M. Cederlöf, "Podium acoustics for the symphony orchestra," Master's thesis, Royal Institute of Technology, Stockholm, 2006.

[5] Y. H. Kim, C. K. Seo, and J. Y. Jeon, "Evaluation of stage acoustics in concert halls by investigating performer's preference," *Proc. 19th Int. Congr. Acoust., Madrid, Spain*, 2007.

[6] A. Guthrie, *Stage Acoustics for Musicians: A Multidimensional Approach using Ambisonics Technology*. New York: Rensselaer Polytechnic Institute, 2014.

[7] K. Ueno and H. Tachibana, "Experimental study on the evaluation of stage acoustics by musicians using a 6-channel sound simulation system," *Acoust. Sci. Tech.*, vol. 3, no. 24, pp. 130–138, 2003.

[8] F. Wendt and R. Höldrich, "Precedence effect for specular and diffuse reflections," *Acta Acustica*, vol. 5, no. 1, 2021.

[9] Z. Schärer Kalkandjiev and S. Weinzierl, "An Instrument for Measuring the Perception of Room Acoustics from the Perspective of Musicians: The Stage Acoustic Quality Inventory (STAQI)," in *Proc. of DAGA*, (Munich, Germany), pp. 1747–1751, 2018.

[10] R. Wenmaekers, *Stage acoustics and sound exposure in performance and rehearsal spaces*. PhD Thesis, Technical University Eindhoven, 2017.

[11] A. H. Marshall, D. Gottlob, and H. Alrutz, "Acoustical conditions preferred for ensemble," *J. Acoust. Soc. Am.*, vol. 64, pp. 1437–1442, 1978.

[12] G. Miller, S. Pfeiffer, D. Schuette, C. Giegold, and L. Brill, "Orchestral Preferences for Discrete Overhead and Side Wall On-Stage Reflections," in *Proc. of the Int. Symp. on Room Acoustics*, (Amsterdam, Netherlands), pp. 299–303, 2019.

[13] L. Shtrepi, A. Astolfi, S. Pelzer, R. Vitale, and M. Rychtarikova, "Objective and perceptual assessment of the scattered sound field in a simulated concert hall," *J. Acoust. Soc. Am.*, vol. 138, no. 3, pp. 1485–1497, 2015.

[14] D. Schröder, *Physically Based Real-Time Auralization of Interactive Virtual Environments*. PhD thesis, RWTH Aachen, 2011.

[15] F. Brinkmann, A. Lindau, S. Weinzierl, G. Geissler, and S. Van De Par, "A high resolution head-related transfer function database including different orientations of head above the torso," in *Proc. of the Int. Conference on Acoustics: AIA-DAGA 2013*, (Merano, Italy), pp. 596–599, 2013.

[16] S. Weinzierl, M. Vorlaender, G. Behler, F. Brinkmann, H. von Coler, J. Kraemer, A. Lindau, M. Pollow, and N. R. Shabtai, "A database of anechoic microphone array measurements of musical instruments," *available at: http://dx.doi.org/10.14279/depositonce-5861.2*, 2017.

[17] T. J. Cox and P. D'Antonio, *Acoustic absorbers and diffusers: theory, design and application*. London ; New York: Taylor & Francis, 2nd ed., 2009.

[18] A. Lindau and S. Weinzierl, "Assessing the Plausibility of Virtual Acoustic Environments," *Acta Acustica united with Acustica*, vol. 98, no. 5, pp. 804–810, 2012.

[19] Z. Schärer Kalkandjiev and S. Weinzierl, "The influence of room acoustics on solo music performance: An experimental study," *Psychomusicology: Music, Mind, and Brain*, vol. 25, pp. 195–207, 2015.

[20] jamovi, *The jamovi project*. Computer Software, 2022.

[21] M. Gallucci and S. Jentschke, *SEMLj: jamovi SEM Analysis*. jamovi module, 2021.

[22] E. Kahle, "Acoustic feedback for performers on stage – return from experience," in *Proc. of the International Symposium on Musical and Room Acoustics*, (Buenos Aires, Argentina), 2016.