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The Influence of Room Acoustics on Solo Music Performance: An Experimental Study

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Abstract

For the performance of music, the room surrounding the musician and his audience plays an important role: it acts as an acoustical transformer, modifying the sound and thus influencing the perception of player and listeners. For the active performer, this entails a complex interaction between the production and perception of sound.

The aim of this experimental study was to investigate the effect of specific room acoustical conditions on aspects of music performance such as ‘tempo’, ‘loudness’, ‘dynamic bandwidth’ or ‘timbre’. Computer models of 14 rooms were generated, corresponding to real halls and representing typical concert venues. Simulated measurements were carried out to determine room acoustical parameters according to ISO 3382-1 as well as new parameters for stage acoustics. Solo performers were recorded while playing in corresponding virtual acoustic environments generated by dynamic binaural synthesis. From these recordings, audio features were extracted to calculate descriptors for different attributes of the musical performance. The influence of room acoustical parameters on performance properties as well as the effect of the musical content and the played instrument was then analyzed based on hierarchical linear models. The analysis revealed distinct concepts of adjustment to room acoustical conditions as well as great individuality with respect to the interaction of musicians with their room acoustical environment.

Keywords: Music performance; room acoustics; performance analysis; binaural synthesis

1 Introduction

For the sounding realization of music, the spatial environment plays a crucial role since its room acoustical properties affect the perception of both audience and musicians. If one assumes that players have an inner representation of the intended sound to be conveyed to the listener (Gabrielsson, 1999), it is likely that they adapt their way of playing to the surrounding room to achieve the sound they have in mind. In some of the famous music treatises of the 18th and 19th centuries (Quantz, 1983; Spohr, 1833; Czerny, 1839) as well as in more recent works (Flesch, 1928; Borciani, 1973; Galamian, 1983) there are numerous recommendations for the use of special playing techniques in specific room acoustical surroundings. Even though most musicians seem to be aware of the influence of the room acoustics on their sound production, it is not clear to what extent these instructions are followed in practice. Some performers even reject any adjustments of their way of playing to the room acoustical conditions (Flesch, 1928; Blum, 1987).

In search of empirical evidence for the effect of room acoustics on music performance, Winckel (1962) measured sound pressure and tempo (derived from the total playing time) during performances of the Cleveland Orchestra in various concert halls. Interestingly, he observed no linear relation between Reverberation Time and tempo, but rather a maximum tempo in halls with particularly good hearing conditions. In a laboratory study with pianists playing in three different rooms, von Békésy (1968) found an increase in the dynamic strength (derived from the vibration amplitude of the piano body) with decreasing Reverberation Time while the maximum dynamic range was found in intermediately reverberant conditions. It is noteworthy that the adjustments were less pronounced when the performers played unfamiliar pieces and when they were non-professionals. Von Békésy's results were confirmed by Bolzinger, Warufsel, and Kahle (1994), who found a negative correlation of the average velocity of MIDI piano performances with the Reverberation Time and late reverberation level of a room with variable acoustics. Surprisingly, the tempo of the played pieces was not affected by the room acoustical conditions in this investigation. In a study with different instrumentalists playing short musical phrases in sound fields simulated by a 6-channel-loudspeaker system, phrase duration, A-weighted sound pressure level, fluctuations of fundamental frequency and SPL as well as spectral features were measured to characterize the performance parameters tempo, dynamic strength, vibrato and timbre. The analysis showed that these parameters were varied with the room acoustical conditions, but the manner of adjustment was dependent on the played instrument in most cases (Ueno, Kato, & Kawai, 2007; Kato, Ueno, & Kawai, 2007; Kato, Ueno, & Kawai 2008). Especially for fast pieces, the tempo was observed to be reduced in both very reverberant and anechoic conditions. Moreover, some musicians adjusted their strength of playing in a similar way (Kato et al., 2007). With respect to specific room acoustical parameters, Ueno, Kato, and Kawai (2010) implied that the stage parameters Early Support and Late Support (Gade, 1992) were the best indicators of the room acoustical influence on dynamic strength.

The authors of the current investigation carried out a case study with a renowned violoncello soloist who was recorded during a concert tour in different halls (Schärer Kalkandjiev & Weinzierl, 2013). Using performance parameters based on audio features as predictors for the perceptual properties of musical performances (see section 2.2), they observed that the tempo was negatively correlated with the squared Reverberation Time of the concert spaces, reproducing the findings of Kato et al. (2007). In contrast to the results of previous studies, they found the predicted dynamic strength to increase with Reverberation Time, and both dynamic strength and dynamic bandwidth to decrease with the Sound Strength of the halls. The most obvious adjustments were related to timbre attributes, which were influenced by the Reverberation Time and the stage parameter Late Support.

The complex and partly conflicting observations on the interaction of room acoustics and musical performance mentioned above call for further investigations aiming at a best possible ecological validity with respect to the performance situation while at the same time employing maximum variance and sufficient control over the experimental room acoustical conditions. Moreover, the individual performance concepts of musicians should be taken into account to explain some of the differences between performers.

In the study presented here, the aim was to achieve this by a plausible yet minimally invasive simulation of performance environments with greatly varying acoustic conditions, represented by computer models and auralized by means of dynamic binaural synthesis. Twelve performers of six orchestral instruments were recorded while performing extended musical excerpts in these virtual rooms. A software-based analysis of the recordings was employed to quantify different characteristics of music performance while room acoustical parameters were determined in the room models. This was the basis of a statistical analysis, taking into account not only the effect of room acoustical conditions, but also the influence of the musical content, the played instrument and the performers' individuality in their way of playing.

2 Methods

2.1 Experimental Design

So far, few studies have taken into account more than one solo instrument when investigating the influence of room acoustics on music performance. However, the played instrument is likely to have an effect on the way musicians adjust their performance to the room acoustical environment. Thus, six typical orchestral instruments were included in the current experiment, covering different registers of strings, woodwind and brass: violin, cello, clarinet, bassoon, trumpet and trombone. Two professional performers of each of these instruments were asked to play excerpts (approx. 1 min) of two pieces of their choice with calm and lively characters, respectively. This categorization was meant to enable a comparison between pieces of different tempo, even though the musicians did not play exactly the same music (see Table 1).

Table 1
Pieces played by the musicians

Instrument	**Piece**	**Composer**	**Bars**	**Basic tempo**
Violin 1	Concert for violin Nr. 5 KV 219, 1st movement	W. A. Mozart	46-88	fast
	Concert for violin op. 35, 1st movement	P. I. Tchaikovsky	23-50	slow
Violin 2	Sonata for violin solo Nr. 6 op. 27, 1st movement	E. Ysaye	1-40	fast
	Sonata for violin solo BWV 1005	J. S. Bach	1-8	slow
Cello 1	Suite Nr. 5 for violoncello solo BWV 1011, gigue	J. S. Bach	1-72	fast
	Suite Nr. 5 for violoncello solo BWV 1011, sarabande	J. S. Bach	1-20	slow
Cello 2	Suite Nr. 1 for violoncello solo BWV 1007, prélude	J. S. Bach	1-22	fast
	Suite Nr. 1 for Violoncello solo BWV 1007, sarabande	J. S. Bach	1-15	slow
Clarinet 1	Sonata for clarinet and piano, 3rd movement	F. Poulenc	1-33	fast
	Concert for clarinet (Darmstädter), 1st movement	K. Stamitz	1-20	slow
Clarinet 2	Three pieces for clarinet solo, 2nd movement	I. Stravinsky	whole movement	fast
	Three pieces for clarinet solo, 1st movement	I. Stravinsky	1-19	slow
Bassoon 1	Concert for bassoon KV 191, 1st movement	W. A. Mozart	35-71	fast
	Concert for bassoon KV 191, 2nd movement	W. A. Mozart	1-18	slow
Bassoon 2	Fantasia Nr. 8 for bassoon solo	B. de Selma	1-31	fast
	Fantasia Nr. 7 for violin solo, 1st movement	G. Ph. Telemann	1-11s	slow
Trumpet 1	Suite Nr. 1 for violoncello solo BWV 1007, gigue	J. S. Bach	1-20	fast
	Suite Nr. 2 for violoncello solo BWV 1008, sarabande	J. S. Bach	1-20	slow
Trumpet 2	Trumpet voluntary	J. Clarke	9-16 / 25-32 / 41-56	fast
	Pavane op. 5	G. Fauré	1-16	slow
Trombone 1	Morceau Symphonique op. 88	A. Guilmant	43-80	fast
	Romance	C. M. von Weber	30-58	slow
Trombone 2	Concertino Petite	J. Cimera	6-24	fast
	Vocalise #1	M. Bordogni	4-28	slow

Table 2
Room acoustical parameters used as independent variables

Room acoustical parameters		**Subjective criteria**
Reverberation Time[a]	RT	Duration of reverberation
Early Decay Time[a]	EDT	Reverberance, reverberant energy
Late Support[a]	ST_{late}	
Late Sound Strength[b]	G_l	
Early Support[a]	ST_{early}	Ensemble conditions, early energy
Early Sound Strength[b]	G_e	
Clarity[a]	C_{80}	Transparency of sound
Sound Strength[a]	G	Subjective sound level
Bass Ratio[c]	BR	Warmth
Bass Strength[c]	G_{125}	

Note. [a]*ISO 3382-1* (2009); [b]*Dammerud* (2009); [c]*Beranek* (2004).

Table 2 shows the room acoustical parameters that were used as independent variables in this study. Only perceptually meaningful measures could be expected to have an influence on music performance, so seven parameters recommended by Gade (2013) to characterize the room acoustical conditions for musicians were used: EDT, RT, C_{80}, ST_{early}, ST_{late}, G_e, G_l (ISO 3382-1, 2009; Dammerud, 2009). Moreover, the independent variables included the Sound Strength, G, as a measure for the subjective sound level, as well as two parameters describing timbral aspects of the room: the Bass Ratio BR and – since the subjective relevance of BR has been doubted (Beranek, 2004; Gade, 2007; Schärer Kalkandjiev & Weinzierl, 2013) – the Bass Strength, G_{125} (Beranek, 2004). The parameters were calculated based on simulated room impulse responses, as described in section 2.3. Since it was crucial for this study to capture the room acoustical conditions from the performers' point of view, the source-receiver setup was to reproduce the typical position of a musician and his instrument on stage during a solo performance. Thus, the room acoustical parameters were measured on a central stage position and with sources conforming to the directivity of the investigated instruments (see section 2.3).

The properties of each music performance as dependent variables in the experiment were determined from recordings made during the experiments. The method of quantifying specific performance attributes from these recordings is described in section 2.2.

2.2 Recordings and Performance Analysis

The performances of the musicians were recorded with a miniature microphone (Sennheiser MKE 1) attached directly to the instruments, as shown for the violin in Figure 1. In this way, a constant distance between the microphone and the instruments was ensured and sound level fluctuations caused by instrument movements were prevented. The experiment took place in the fully anechoic chamber of the TU Berlin (V = 1850 m^3, f_c = 63 Hz), so the recordings were not influenced by the acoustics of the experimental room.

Figure 1. Violinist playing in a simulated concert hall, wearing extra-aural headphones with the recording microphone (marked by the arrow) attached to his instrument.

When music performances are described on the basis of physical measurements, a major difficulty is to identify the most relevant aspects of music performance and to select the corresponding audio features. This is illustrated by the fact that the studies mentioned in section 1 used a wide range of methods to quantify the dynamic strength of the performances alone: vibration amplitude (von Békésy, 1968), MIDI velocity (Bolzinger et al., 1994) and A-weighted sound pressure level (Winckel, 1962; Ueno et al., 2007). As Nakamura (1987) showed, the perception of musical dynamics not only depends on intensity but also on timbre and musical context, so the use of simple intensity measures can be called into question. Moreover, the majority of investigations reviewed above used the duration of musical phrases as an indicator for their tempo. It was demonstrated by Repp (1994), though, that listeners' perception of tempo is strongly related to the timing microstructure in music performances.

The method employed in this study aiming at a perceptually meaningful, quantitative analysis of different performances was already used in a previous investigation (Schärer Kalkandjiev & Weinzierl, 2013) and is described in the following. In a first step, audio features were extracted from the 336 recordings (average duration 67.12 s) made during the experiment by software-based audio content analysis (Lerch, 2009). By employing a dynamic time warping algorithm, the software found the best alignment between the audio signal and a MIDI representation of the score. This resulted in onset times for all played notes in a piece, which were verified auditorily and manually corrected if necessary. For the description of loudness- and timbre-related properties, the software yielded the features listed in Table 3 for each musical event identified by the onset detection, i.e. each note in the score. The extracted tempo-, loudness- and timbre-related features were used as independent variables in regression models in order to predict perceptual qualities of music performances. The models are based on a study by Weinzierl and Maempel (2011) who had used a wide variety of audio features extracted from recorded performances of three different music pieces to predict the ratings of the same recordings given by an expert panel, using a consensus vocabulary for the description of music performances which was previously agreed upon. Not all of the performance attributes could be predicted equally well, so in the study presented here, only those regression models with more than 50% explained variance were considered. Thus, the eight performance attributes shown in Table 4 were calculated for the recordings of music performances in different room acoustical environments. In order to clearly distinguish these attributes from everyday use of the same terminology, they are put in single quotation marks in the following.

Table 3
Loudness and timbre features extracted from the recordings

Loudness features	Timbre features
Zwicker loudness (DIN 45631)	Spectral roll-off (SR)
Zwicker loudness (ITU-R BS. 1387)	Spectral flux (SF)
Loudness (ITU-R BS. 1770)	Spectral centroid (SC)
dB (A)	Spectral spread (SS)
RMS	Mel frequency cepstral coefficients 0-4 (MFCCs)
Volume unit meter	

Note. SR: Measure for signal bandwidth; SF: Simplified measure for roughness; SC: Gravity center of spectral energy; SS: Measure for energy spread around SC; MFCCs: Components of spectral envelope *(Lerch, 2012)*.

Table 4
Investigated performance attributes

Performance attributes	Expl. Var. [%]
'Tempo'	89.5
'Agogic'	53.2
'Dynamic strength'	62.8
'Dynamic bandwidth'	67.0
'Timbre (soft – hard)'	63.7
'Timbre (dark – bright)'	56.8
'Timbre (lean – full)'	68.2
'Timbral bandwidth'	65.4

Note. Variance explained by regression models with technically derived audio features as predictors for performance attributes defined by expert listeners *(Weinzierl & Maempel, 2011)*.

2.3 Room Acoustical Models

The room acoustical computer models used for the experiment were generated with EASE 4.3. The 14 models shown in Figure 2 and listed in Table 5 represent typical performance venues which were inspired by existing halls (Weinzierl, 2002; Hidaka & Nishihara, 2004; Beranek, 2004; Schärer Kalkandjiev & Weinzierl, 2013) and cover a broad range of room acoustical properties. Three of the rooms were used in two versions (denoted as 'a/b' in Table 5) with different absorption properties, i.e. with different frequency dependent Reverberation Times.

For an overview of the room acoustical conditions in the halls, Figure 3 (solid lines) shows room acoustical parameters frequency averaged according to ISO 3382-1 (2009) and measured with an omnidirectional source in the center of each stage, 1.5 m from its edge. In accordance with the source-receiver configuration required for the support parameters (ISO 3382-1, 2009), the receiver position was defined at 1 m behind the source, facing the audience. Both transducers were placed at a height of 1 m. The only parameters that show little variation in Figure 3 are G, G_e and G_{125}, due to the dominance of the direct sound in the measurements at this short distance between source and receiver. The correlations between the frequency-averaged parameters are given in Table 6.

Table 5

Features of the room models

Abbr.	Purpose	Volume [m^3]	Stage size [m^2]
CHA1	Chamber hall	2335	56
CHA2 a/b	Chamber hall	3233	85
CON1 a/b	Concert hall	21661	109
CON2	Concert hall	10261	186
CHU a/b	Baroque church	12530	55
OPR	Opera	14862	97
ANC	Chamber hall	5714	83
GGA	Concert hall	12553	108
PLE	Historical concert hall	900	29
TJV	Theatre	11175	67
WMH	Chamber hall	2773	32

Note. The affix “a/b” denotes the halls generated with two different versions of absorption properties.

Table 6

Pearson correlation between the frequency-averaged room acoustical parameters

	EDT	RT	C_{80}	G	ST_{early}	ST_{late}	G_e	G_l	BR	G_{125}
EDT	1									
RT	-0.08	1								
C_{80}	-0.88**	-0.24	1							
G	0.78**	-0.02	-0.83**	1						
ST_{early}	0.78**	-0.08	-0.82**	0.87**	1					
ST_{late}	0.92**	-0.03	-0.96**	0.88**	0.87**	1				
G_e	0.61*	-0.08	-0.67**	0.96**	0.83**	0.75**	1			
G_l	0.88**	0.21	-0.99**	0.87**	0.84**	0.97**	0.73**	1		
BR	0.18	-0.40	0.02	0.27	0.11	0.11	0.32	0.02	1	
G_{125}	0.37	-0.03	-0.32	0.12	0.15	0.32	0.02	0.29	0.32	1

Note. Parameters were measured on the stages of the computer models with 1 m distance between omnidirectional source and receiver, both at 1 m height.
** $p < 0.01$, two-tailed. * $p < 0.05$, two-tailed.

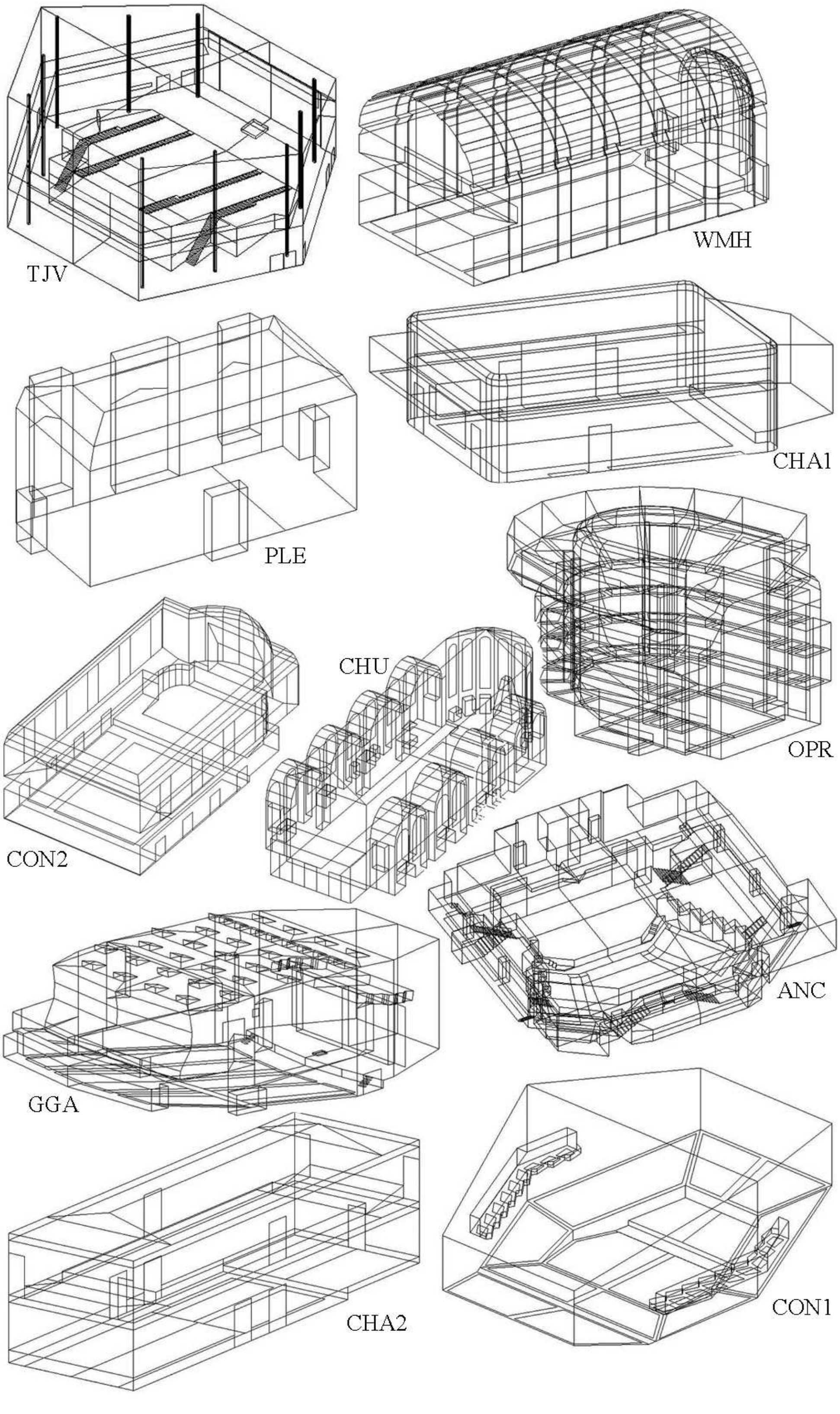

Figure 2. Computer models for room acoustical environments simulated in the experiment. See Table 5 for abbreviations.

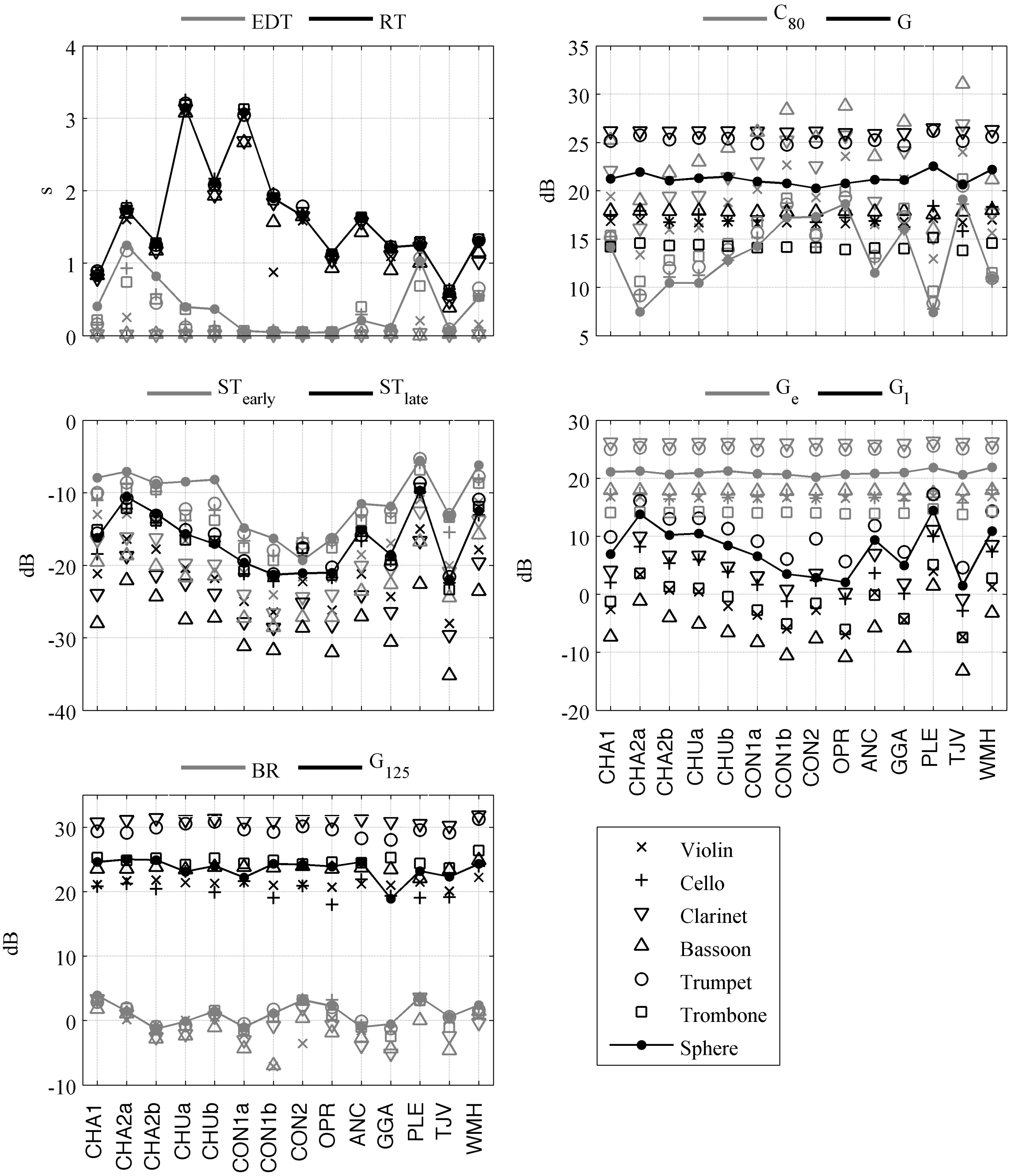

Figure 3. Frequency-averaged room acoustical parameters (gray and black) measured on the stages of the room models using an onmi-directional source (sphere) as well as sources with the directivity of the investigated instruments. Sound Strength parameters *G*, G_e and G_l are normalized to a distance of 1 m between source and receiver.

For the statistical analysis of the relationship between room acoustical conditions and music performance, the room acoustical parameters were determined with directional sources. For these measurements, the receiver was defined in the center of the stage, 2.5 m behind the stage edge and at a height of 1.2 m, which was assumed as the typical ear height of a seated person. A directivity database by Schneider (2011) in third-octave bands, based on microphone array measurements of all orchestral instruments (Pollow, Behler, & Schultz, 2010), was used for representing the played instruments. The positions of the directional sources in relation to the receiver point were established by estimating the typical distance between the acoustical center of the respective instrument and the performers' ears (see Table 7). Figure 4 shows the frequency-averaged room acoustical parameters of each room model and instrument.

Table 7

Position of directional sources in the computer models

Instrument	x [cm]	y [cm]	z [cm]
Violin	20	-20	0
Cello	0	-40	-60
Clarinet	0	-20	-20
Bassoon	0	-20	-20
Trumpet	0	-50	0
Trombone	20	-30	0

Note. Coordinates are given relative to a receiver 1.2 m above the floor. Positive x-values refer to the left hand side, negative y-values refer to the front side, both as viewed from the receiver.

2.4 Acquisition of Binaural Room Impulse Responses

The binaural room impulse responses (BRIRs) required for the auralizations were generated from the room acoustical computer models in three steps. First, reflectograms were produced in each of the 14 room models, using directional sound sources and source-receiver distances as described above. The angle of impact, the arrival time and the sound level in third octave bands from 100 Hz to 10 kHz for each reflection was thereby recorded.

Second, room impulse responses were generated for each reflection by calculating a frequency and a phase spectrum. For the former, the third octave band levels of the reflectogram were interpolated with cubic splines and an extrapolation was employed below and above the highest bands, assuming a decrease of -24 dB per octave below 20 Hz and a decrease of -3 dB per octave above 10 kHz. Subsequently, a minimum phase was reconstructed for each frequency spectrum to generate the impulse response by inverse Fourier transformation.

Third, each impulse response – representing one reflection – was convolved with a head related transfer function (HRTF) corresponding to the angle of sound impact stored in the reflectograms. For this, a database of HRTFs (Brinkmann, Lindau, Weinzierl, Geissler, & van de Par, 2013) with high spatial resolution was used. The direct sound was excluded at this stage because it was not auralized in the experiment, as explained below. The convolution results were added up, yielding one complete binaural room impulse response. This step was repeated with HRTFs for head rotations of ±50° and head elevations of −30° to 21° in steps of 2° and 3°, respectively. According to Lindau and Weinzierl (2009), this resolution is below the minimum grid resolution necessary for the dynamic binaural synthesis of music signals.

The described procedure yielded one dataset of 918 BRIRs for each room model and each instrument, with 84 datasets in total.

2.5 Auralization

The room acoustical environments described above were auralized by dynamic binaural synthesis (Lindau, Hohn, & Weinzierl, 2007), providing a highly plausible simulation of room acoustical environments (Lindau & Weinzierl, 2012). Since the musicians actively participated in the simulation, producing the sound to be recorded and used for the simulation, only the response of the room was simulated and not the direct signal of the instruments (see setup in Figure 4). The appropriate binaural room impulse response was selected by head tracking (Polhemus Patriot) and convolved with the anechoic input signal in real-time. The simulation was presented to the performers with extra-aural headphones (AKG K-1000), providing almost perfect free-air equivalent coupling (Møller, 1992) and barely impeding the instrument's direct sound path to the performer's ears (see Figrue 1). The frequency responses of the recording microphone and the headphones were equalized, the latter was compensated individually for each musician (Lindau & Brinkmann, 2012).

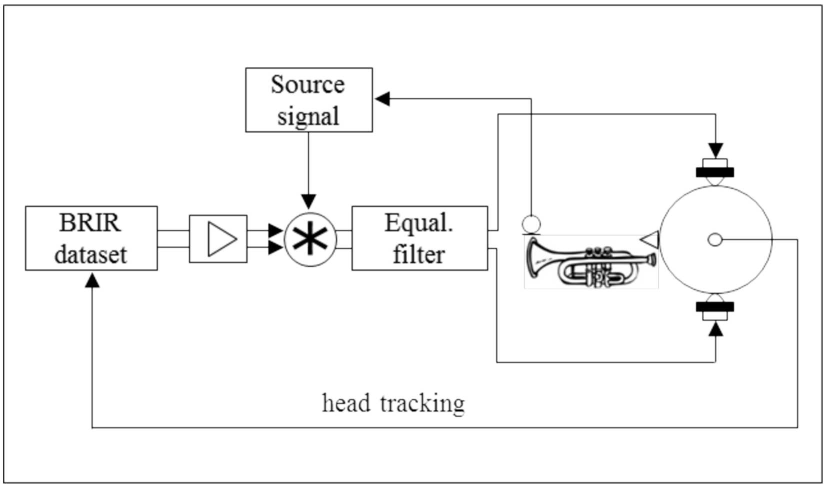

Figure 4. Technical setup of the experiment. ∗ denotes the convolution of source signal and loudness calibrated BRIR.

2.6 Experimental Procedure

The performers (10 male, 2 female) aged between 21 and 48 years (average: 32 years) attended the experiment in two sessions with seven rooms each. They had between 5 and 30 years of experience in performing on concert hall stages (average: 20 years) and were thus acquainted with varying room acoustical conditions. After a measurement of the individual headphone transfer function required for equalization, the sound level of the simulation was calibrated. While the level between the individual rooms was correct due to an identical sound power of the sources in all computer models, the level of the simulations relative to the direct sound needed to be determined. For this purpose, a single sound event of each instrument was recorded with both the instrument microphone and a dummy head (Neumann KU 81i) located at 5 m distance from the musician. Then, the headphones were placed on the dummy head and the previously recorded sound was played through a binaural simulation of an anechoic chamber with a source-receiver distance of 5 m. This simulation was again recorded with the dummy head, and the RMS level difference of both dummy head recordings yielded a scaling factor for the binaural simulations of the concert halls. Prior to the recording session, the performers were given 10 minutes to become familiar with each virtual room. Then, they were recorded playing excerpts of two music pieces (see Table 1). Finally, the musicians were asked to describe their way of playing and impression of the room acoustics in a short interview. The warm-up, the recording of the two pieces and the interview were repeated in each of the randomly presented virtual rooms. One experimental session lasted between three and four hours with an extendedbreak in the middle of a session and additional pauses whenever necessary.

2.7 Statistical Analysis

The statistical analysis of the experiment was to reveal the effect of ten room acoustical parameters – measured individually with the source-directivity of six instruments – on eight performance attributes determined from recordings of twelve musicians playing two pieces each. Because of the apparent nested data structure, a multivariate hierarchical linear model (HLM) was employed for the analysis (Hox, 2010). In such multilevel regression models, the variance of the data is estimated separately on each level (here: rooms, musicians, pieces) of the nested structure and the effect of the independent variables is estimated more correctly.

As shown in Table 6, there are high correlations between some of the room acoustical parameters. Therefore, the number of predictors in the HLM needed to be reduced in order to avoid multicollinearity. Hence, six principle component analyses (PCAs) were performed with the room acoustical parameters measured for each source directivity. The criterion for the number of components to be extracted was set to a minimum of 95 % cumulative proportion of explained variance. After varimax rotation all of the PCAs yielded five components explaining between 97.26 % (clarinet) and 98.70 % (cello) of the acoustical variance measured in the modelled concert spaces. Table 8 shows the loadings on the five components for the PCA carried out with the parameters for cello directivity. The component loadings of the PCAs for the other instruments were highly similar. The room acoustical parameters with the highest loading on each of the five components were selected as predictors for the multilevel analysis: ST_{late}, G_e, RT, BR and G_{125}. In the case of the first component, some of the PCAs yielded C_{80} or EDT as the highest loading variable. Because of the high correlation between ST_{late} and these measures (see Table 6), ST_{late} was selected for all instruments. The choice of ST_{late} also enabled a direct comparison with previous work (Schärer Kalkandjiev & Weinzierl, 2013). Hence, the ten possible room acoustical predictors were reduced to five salient parameters that were entered as explanatory variables into the multilevel analysis.

Table 8

Loadings and explained variance of a PCA with varimax rotation conducted with ten room acoustical parameters measured with a directional source corresponding to a cello

	Components				
Variables	1	2	3	4	5
ST_{late}	**<u>0.96</u>**	0.22	-0.00	0.15	0.07
C_{80}	**-0.94**	-0.18	-0.19	-0.22	-0.06
ST_{early}	**0.90**	0.18	-0.30	0.12	0.02
G_l	**0.90**	0.30	0.19	0.22	0.09
EDT	**0.89**	0.34	-0.16	-0.11	-0.04
G_e	0.33	**<u>0.89</u>**	0.10	0.16	0.25
G	**0.50**	**0.81**	0.11	0.13	0.24
RT	-0.05	0.12	**<u>0.94</u>**	0.21	-0.20
G_{125}	0.23	0.17	0.22	**<u>0.92</u>**	-0.13
BR	0.05	0.37	-0.24	-0.15	**<u>0.88</u>**
Expl. Var. [%]	46.32	19.52	12.13	11.04	9.69

Note. Factor loadings > 0.5 are marked bold, highest factor loadings are underlined.

These predictors varied on the musician level of the HLM since the parameters were individually measured for the instruments. However, the absolute difference between the parameters for the six instruments was not of interest. The focus rather lay on the differences among the acoustical properties of the performance venues experienced by the performers, so all room acoustical parameters were z-transformed within the measurements for the individual instruments.

3 Results

3.1 Data structure

First, the proportion of variance in the response data at the different levels was compared for each of the eight response variables (see Table 4). For this purpose, the variances on room, musician and piece level $\sigma^2_{v\,|\,\text{room}}$, $\sigma^2_{v\,|\,\text{musician}}$, and $\sigma^2_{v\,|\,\text{piece}}$ were estimated in univariate 3-level intercept-only HLMs – i.e. in models with no regressors that only consider the level structure – for each performance attribute. The results in Table 9 show that the variance on the room level is very small compared to the variance on the other levels for all response variables. In some cases, $\sigma^2_{v\,|\,\text{room}}$ was even too small to be estimated, so 2-level models (musicians, pieces) were utilized here. As explained above, it is an intrinsic feature of HLMs to consider the nested structure of data, so $\sigma^2_{v\,|\,\text{room}}$ indicates the variance across rooms when the respective performance attribute is averaged across musicians and pieces. $\sigma^2_{v\,|\,\text{musician}}$, on the other hand, is to be understood as the variance across the interaction of musicians and rooms. The results in Table 9 thus imply that the variance of the musicians' individual adjustments to the room acoustics was greater than the variance of their averaged adjustments, i.e. that the players' reaction patterns to the room acoustical environment were highly individual. Since $\sigma^2_{v\,|\,\text{room}}$ was so small for all performance attributes, indicating that the room level was not relevant in the hierarchical structure, this level was omitted in the further analysis (Hox, 2010, p. 18).

Table 9

Comparison of variance on different levels of intercept-only HLMs for investigated performance attributes

Response Variable v	$\sigma^2_{v\,|\,\text{room}}$	$\sigma^2_{v\,|\,\text{musician}}$	$\sigma^2_{v\,|\,\text{piece}}$
Tempo	0.02	0.12	0.86
Agogic	-	0.21	0.79
Dynamic strength	-	0.28	0.71
Dynamic bandwidth	-	0.22	0.78
Timbre (soft-hard)	-	0.39	0.61
Timbre (dark-bright)	0.01	0.17	0.82
Timbre (lean-full)	0.02	0.10	0.88
Timbral bandwidth	0.03	0.03	0.94

Note. $\sigma^2_{v\,|\,\text{piece}}$ contains both piece and unexplained error variance.

3.2 Investigated Hierarchical Linear Models

In previous studies there were indications of a quadratic relationship between Reverberation Time and tempo (Kato et al., 2007; Schärer Kalkandjiev & Weinzierl, 2013), dynamic strength (Kato et al., 2007), dynamic bandwidth (von Békésy, 1968) as well as timbre attributes (Schärer Kalkandjiev & Weinzierl, 2013) of performances. To consider this evidence in the current study, two univariate HLMs for each performance attribute were calculated, using the linear and the squared Reverberation Time as sole predictor, respectively. To find the more suitable regressor (linear or squared), Akaike's Information Criterion (AIC) of both models was compared for each performance attribute. The models were calculated with the full maximum likelihood method, since non-nested models were compared here (Hox, 2010, p. 50). The AICs of the models were similar but yielded a preference for the squared Reverberation Time regarding 'agogic', 'dynamic strength, 'timbre (dark – bright)', 'timbre (lean – full)' and 'timbral bandwidth' and for the linear Reverberation Time regarding 'tempo', 'dynamic bandwidth' and 'timbre (soft – hard)'. Thus, RT^2 was entered as predictor for the former five and RT as predictor for the latter three performance attributes in the finally calculated multivariate HLM. The other four independent variables (G_e, ST_{late}, BR, G_{125}) were used as linear predictors.

The parameters of this HLM (M1) were calculated with the restricted maximum likelihood method with standardized independent and dependent variables. Figure 5 (black *) shows the standardized regression coefficients with 95% confidence intervals (CIs) for each performance attribute. They illustrate the extent and significance of the effect of each room acoustical predictor on the response variables.

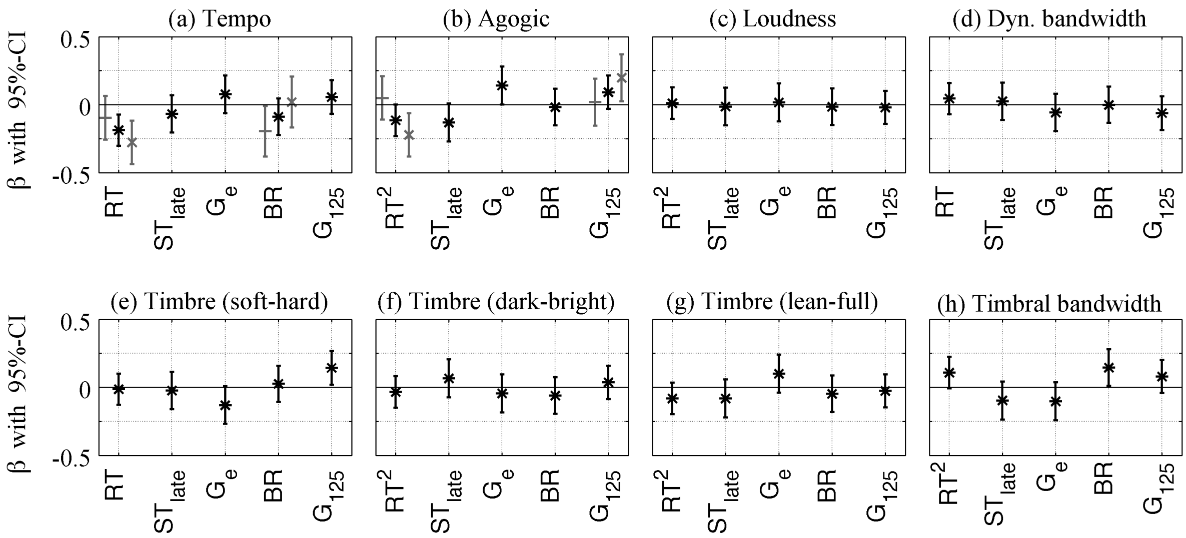

Figure 5. Standardized regression coefficients with 95% confidence intervals (CIs) for the five room acoustical predictors (x-axes) and the eight performance attributes (a-h). The black markers (*) show the coefficients averaged across musicians and pieces. The gray markers show the coefficients for considerable differences between fast (-) and slow (x) pieces. CIs not crossing the zero-line indicate significant coefficients ($p < 0.05$).

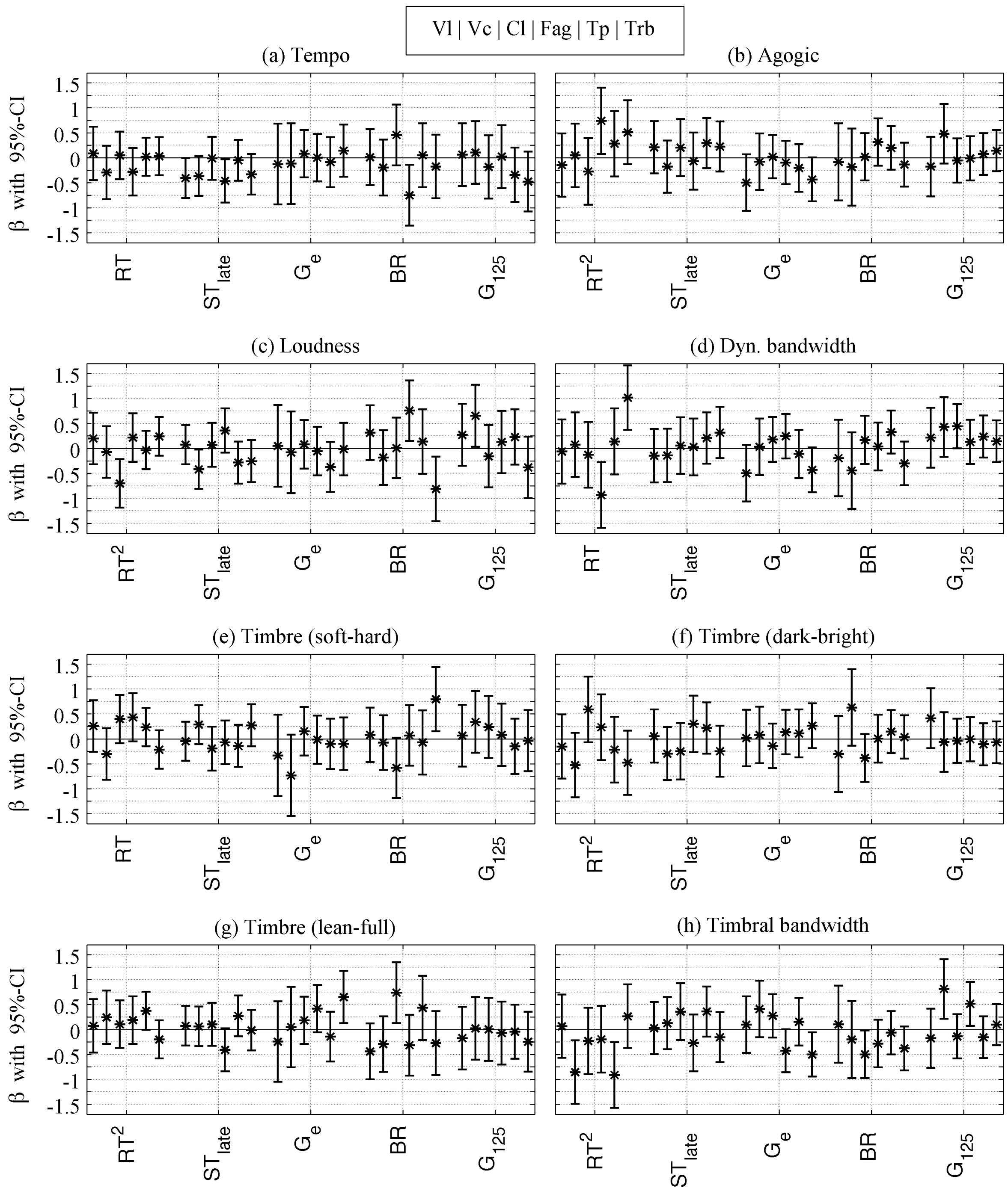

Figure 6. Standardized regression coefficients with 95% confidence intervals (CIs) for the five room acoustical predictors (x-axes) separately predicting the instruments' performance attributes (a-h). Coefficients for each predictor from left to right: violin (Vl), cello (Vlc), clarinet (Cl), bassoon (Fag), trumpet (Tp), trombone (Trb). CIs not crossing the zero-line indicate significant coefficients ($p < 0.05$).

There has been evidence in a previous study (Schärer Kalkandjiev & Weinzierl, 2013) that a musician's reaction to the room acoustical environment partly depends on the musical content. A factor 'basic tempo' with the values 'slow' and 'fast' was therefore entered into the HLM, since the two pieces played by each performer could be classified in this respect relatively easily (see Table 1). The resulting HLM (M2) yielded no significant difference between the two factor levels for any performance attribute and room acoustical predictor. Figure 5 (gray – and x) shows some interactions between 'basic tempo' and room acoustical parameters that indicate a strong tendency for a difference between both categories. Since the factor introduced here relates to the tempo of the played pieces, it is not surprising that all relevant differences are related to the temporal performance attributes 'tempo' and 'agogic'.

To investigate the effect of the played instrument, a further HLM (M3) with a factor 'instrument' was calculated. The effect of this factor was not significant for all interactions, but as Figure 6 shows, there were large differences between some of the instruments for all performance attributes.

The variance explained on the musician level by model M1 (see above) was calculated according to Snijders and Bosker (1994):

$$R^2_{\text{musician}} = 1 - \frac{\sigma^2_{\text{M1 | musician}} + \dfrac{\sigma^2_{\text{M1 | rest}}}{n}}{\sigma^2_{\text{M0 | musician}} + \dfrac{\sigma^2_{\text{M0 | rest}}}{n}}$$

$\sigma^2_{\text{M1 | musician}}$ and $\sigma^2_{\text{M1 | rest}}$ are the musician level variance and the residual variance of the target model M1. $\sigma^2_{\text{M0 | musician}}$ and $\sigma^2_{\text{M0 | rest}}$ are the variance on the respective levels in an intercept-only model M0 with no predictors. n is the number of groups, i.e. musicians. The variance explained by model M1, in which the room acoustical parameters were used to predict the performance attributes averaged over pieces and musicians, only amounted to 0.41 %. This value is very low compared to the 58.27 % of variance explained by an HLM with room acoustical predictors used in the above mentioned case study by Schärer Kalkandjiev and Weinzierl (2013). However, the fact that the musicians in the current experiment had very individual strategies to adjust their way of playing to the room acoustics, as shown above, needs to be considered. Thus, to obtain a model comparable to the one in the case study, an HLM (M4) with the musician index as a factor was calculated, estimating regression coefficients for the interaction between each individual musician and the room acoustical predictors. The variance explained by this model M4 was 7.64 %, so almost twentyfold more than model M1 (see section 4 for a discussion of this result).

3.3 Musicians' adjustments to room acoustics

Tempo Averaged over musicians and pieces, the 'tempo' chosen by the players was significantly influenced by the Reverberation Time of the concert spaces (Figure 5a, black). As it is often described by performers, they played slower in rooms with long Reverberation Times, presumably to maintain the intelligibility of tone and chord sequences.

When looking at the difference between the basic tempo of the pieces (Figure 5, gray), it is interesting to see that it was mainly the slow piece that was played with reduced 'tempo' in rooms with long Reverberation Time. Interviews held with the performers after playing in each virtual room indicated that many of them focused on playing shorter notes when performing fast pieces in reverberant rooms rather than adapting the 'tempo'. In the case of the cellos, this articulation was even accompanied by an increase in 'tempo', as can be seen in Figure 7, where the interactions between the factor 'basic tempo' and the room acoustical predictors with regard to the performance attribute 'tempo' are shown separately for the instruments. Figure 7 also demonstrates that the violins reacted similarly to the cellist in the case study by Schärer Kalkandjiev and Weinzierl (2013) by significantly decreasing the 'tempo' of the fast piece with increasing Reverberation Time while the 'tempo' of the slow piece was not adjusted.

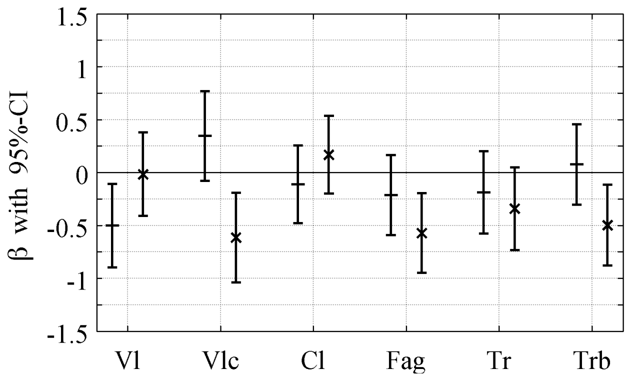

Figure 7. Standardized regression coefficients with 95% confidence intervals (CIs) for RT separately predicting the tempo of each instrument (x-axes) and each 'basic tempo'. -: fast piece; x: slow piece. CIs not crossing the zero-line indicate significant coefficients ($p < 0.05$).

Agogic Although none of the room acoustical parameters had a significant influence on the extent of 'agogic', a strong tendency can be seen that tempo modulations seem to be encouraged by early energy (G_e) and warmth (G_{125}), whereas they tend to be reduced in rooms with much reverberant energy (ST_{late}) and very long as well as very short Reverberation Time (RT^2). Figure 5b (gray) shows that the effect of the Reverberation Time and Bass Strength on 'agogic' were significantly related to the slow pieces only. Possibly, the faster pieces were less suitable for tempo variations.

Dynamic strength None of the room acoustical parameters had a significant effect on 'dynamic strength' when averaged over performers and pieces (Figure 5c). By comparing the different instruments (Figure 6b), only for the cello players there was a significant correlation between the Reverberation Time and 'dynamic strength'. With the squared Reverberation Time used as a predictor here, the results suggest that the cellists increased their strength of playing both for very dry and very reverberant conditions. At least for rooms with a long Reverberation Time, this corresponds to the results of the case study with the cellist (Schärer Kalkandjiev & Weinzierl, 2013). For some of the other instruments, 'dynamic strength' was influenced by ST_{late} and G_{e}, but the response strategies differed among them. Interestingly, only the bassoons and trombones reacted as suggested by previous results (Schärer Kalkandjiev & Weinzierl, 2013) by playing more *piano* in acoustically enhanced environments with high early energy (G_{e}), while the trumpets even followed the opposite strategy.

Dynamic bandwidth In the interviews conducted with the participants of the experiment, many of them remarked that they were able to “play with the dynamics” in rooms that they liked. Regarding the influence of ST_{late} on ‘dynamic bandwidth’ for the different instruments (Figure 6d), the cellos and clarinets showed a strong tendency to increase their dynamic range in acoustically supportive environments (high ST_{late}) – implying that a certain amount of reverberant energy is important for good acoustics and the use of the full instrumental dynamic range –, only the bassoons reacted contrarily.

Timbre With regard to the timbral rendition, the musicians, on average, played ‘softer’ in rooms with high Early Sound Strength (G_{e}, Figure 5e) and significantly ’harder’ in rooms with high Bass Strength (G_{125}, Figure 5e). The first effect might indicate a more relaxed and less forced tone color in acoustically enhanced rooms, while the second effect seems to indicate the intention to compensate for the spectral characteristics of the room. The average ‘timbral bandwidth’ was high in rooms with low reverberant energy (ST_{late}) and high Bass Ratio (*BR,* Figure 5h).

Beyond these average, i.e. largely consistent, reactions, Figure 6e-h reveals large and significant differences among the instruments in the way how their timbre was adjusted to rooms with varying Reverberation Time and Late Support. While the violins felt encouraged to use a ’harder’ and ’brighter’ tonal rendition in rooms with high Late Support, an opposite reaction appeared for the trumpets (Figure 6e-f). And while clarinets and trumpets played ’harder’ in rooms with longer Reverberation Time, the opposite can be seen for cellos and bassoons (Figure 6e).

To explore the importance of the five room acoustical predictors for the individual (rather than the average) performative adjustments, the absolute (rather than the signed) regression coefficients calculated for the individual musicians in model M4 (see above) were averaged for each room acoustical parameter and performance attribute. Table 10 shows the predictors ordered by their average impact on the respective performance attribute, emphasizing the relevance of stage parameters, since it was one of these (G_{e}, ST_{late}) rather than the audience parameters that showed the highest impact on all performance attributes. Furthermore, the Bass Strength (G_{125}) had a greater influence on the musicians’ performance than the Bass Ratio (*BR*) in most cases, indicating that G_{125} might be a better predictor to characterize the timbre properties of a room, at least for musicians on stage.

Table 10

Absolute regression coefficients of room acoustical predictors averaged over musicians

Tempo		Agogic		Loudness		Dyn. bandwidth	
Pred.	β_{mean}	Pred.	β_{mean}	Pred.	β_{mean}	Pred.	β_{mean}
G_e	0.27	G_e	0.35	ST_{late}	0.26	ST_{late}	0.35
BR	0.21	G_{125}	0.25	G_e	0.26	G_{125}	0.29
RT	0.20	RT^2	0.24	RT^2	0.24	BR	0.26
ST_{late}	0.18	ST_{late}	0.24	G_{125}	0.18	G_e	0.26
G_{125}	0.15	BR	0.20	BR	0.17	RT	0.18
Timbre (soft-hard)		Timbre (dark-bright)		Timbre (lean-full)		Timb. bandwidth	
Pred.	β_{mean}	Pred.	β_{mean}	Pred.	β_{mean}	Pred.	β_{mean}
ST_{late}	0.47	ST_{late}	0.36	ST_{late}	0.32	G_e	0.31
G_{125}	0.38	**RT^2**	0.30	G_e	0.29	BR	0.31
G_e	0.36	G_{125}	0.28	BR	0.25	ST_{late}	0.25
RT	0.26	G_e	0.27	RT^2	0.20	G_{125}	0.22
BR	0.19	BR	0.21	G_{125}	0.18	RT^2	0.14

Note. Regression coefficients were calculated separately for the individual musicians in an HLM (M4, see section 3.2) and then averaged as absolute values (β_{mean}). The predictors (pred.) are ordered according to their influence on each performance attribute. Significant interactions between the factor 'musician' and the predictors are highlighted (bold/underlined: $p < 0.01$, underlined: $p < 0.05$).

4 Discussion

The study presented here explored the influence of room acoustics on the performance of professional solo players of different instruments. The experimental setup employed, with a highly plausible simulation of 14 typical concert spaces and the statistical analysis with hierarchical linear models (HLMs), allowed for the investigation of the effect of 5 room acoustical parameters on 8 performance attributes, also considering the influence of the played instrument and the musical content as covariates.

Two patterns of reaction were significant when considering the average performance over all individual musicians involved: playing slower in rooms with long Reverberation Time, which was much more pronounced for slow than for fast pieces, and adjusting the timbre to the spectral characteristics of the room, by playing 'harder' in rooms with a warm sound, as indicated by the Bass Strength G_{125}. In how far the linear relation between Reverberation Time and tempo also holds for very dry rooms is less obvious since previous studies have indicated that the tempo might also be reduced for rooms with a very short Reverberation Time (Kato et al., 2007; Schärer Kalkandjiev & Weinzierl, 2013). The former study, however, also presented particularly dry conditions, i.e. an anechoic environment, whereas for the study presented here *RT* was more than 0.6 s for all rooms.

A substantial result of the investigation was that, beyond those consistent reactions, the response strategies of musicians regarding their room acoustical environment are highly individual. This is indicated by evaluating the amount of variance in the examined performance attributes explained by room acoustical predictors. If adjustments in the performative rendition of all musical pieces are considered on average over all musicians, only 0.41 % of this variance can be explained by the room acoustical parameters used. However, if the "room-effect" is estimated separately for each individual musician, the explained variance in this study amounts to 7.64 %. If this value is compared to the (equally calculated) value of 58 % determined in a field study, where a renowned violoncello soloist was recorded in different concert halls (Schärer Kalkandjiev & Weinzierl, 2013), two issues have to be taken into account related to the experimental approach followed in the current study: First, the room acoustical conditions of real halls can be expected to co-vary with other, visually conveyed properties of the room, such as the room size, the distance between stage and audience, the stage configuration etc., and the entirety of these factors can be expected to have a stronger influence on the performer than the acoustic modality alone. Second, performers confronted with the simulation of a concert venue rather than with the real environment will probably need to assign more cognitive resources to cope with the unusual situation, whereas in the real environments they can resort to intuitive, learned patterns of behavior more easily. This "effort" to get a clear mental idea of the room was repeatedly mentioned by the performers in interviews carried out after the experiment, and it might restrict the amount of performative adjustment no matter how good and plausible the acoustical simulation in the experiment was.

Comparing the five room acoustical predictors selected to represent different dimensions of room acoustical properties with respect to their impact on each individual player's performance attributes, it is the stage parameters Early Sound Strength (G_e) and Late Support (ST_{late}) that have the greatest influence. If the response of musical performers is considered as a criterion for their relevance in the context of stage acoustics, this data can not only be regarded as a confirmation of the currently suggested stage parameters. It might even be appropriate for developing new or optimized parameters, which was, however, not the focus of the current study.

On the basis of advanced virtual acoustic environments , the present paper revealed both general and individual interactions between room acoustical conditions and the performance of different pieces by different instruments and musicians. A statistical analysis of the influence of the factors 'room acoustics', 'basic tempo of the musical piece', 'musical instrument' and 'individual musician' indicated how highly individual the reactions of musicians to their room acoustical environment are. In search for the underlying concepts and performative strategies of these reactions, future work will, on the one hand, test obvious assumptions such as that musicians adapt their performance in order to reach a certain sound effect *in the audience* ("anticipation hypothesis"), and, on the other hand, use the qualitative input provided by interviews conducted with the performers in order to explain the existing observations and to generate specific hypotheses which can be tested with a methodology as presented here.

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