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

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Summary
Since the room acoustical environment has a great influence on the auditory impression of music for both audience and performers, it can be expected that musicians adjust their way of playing to the concert hall acoustics. This interdependence, frequently described by music scholars and performers, was empirically investigated for the first time under professional concert conditions. The renowned cellist Jean-Guihen Queyras was recorded during his performances of the six *Suites for Violoncello Solo* by Johann Sebastian Bach in seven acoustically different concert halls. Using a software-based analysis, seven performance attributes were extracted from the recordings. To determine the acoustical properties of the concert halls, measurements according to ISO 3382-1 were conducted on the stages and in the auditoria and typical acoustical parameters were calculated. Computer models of the seven halls allowed for a reconstruction of the acoustical conditions during the concerts by simulating a sound source with the directivity of a cello as well as the occupied state of the auditoria. By means of a hierarchical linear model, the influence of room acoustics on music performance was investigated in detail. Despite the numerous other external factors present in the real-world concert situations, more than half of the variance of the performance features could be explained by room acoustical parameters, providing evidence of their significant impact on the performance of music.

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1. Introduction

During the performance of music the surrounding environment acts as an acoustical transformer, modifying the sound not only for the audience but also for the musicians themselves. Since their perception can in turn be assumed to influence the way they play, a complex interaction evolves between acoustical production and perception. In the famous music treatises of the 18th and 19th century [1, 2, 3] as well as in modern works [4, 5] there are numerous recommendations for performers about how to adapt to the spatial environment. However, it is unclear to what extent these instructions are actually followed in practice, the more so as not all musicians seem to adopt the concept of a performance being subjected to room acoustical conditions [6, 7].

Early empirical evidence of the influence of reverberation on dynamics was found in a laboratory experiment with pianists playing in rooms with different reverberation times [8]. A decrease in loudness was observed in more reverberant surroundings, while the greatest dynamic range was used under average conditions. The former finding was confirmed by a study with a MIDI grand piano played in a room with variable acoustics [9], whereas, surprisingly, none of the acoustical parameters (reverberation time, late reverberation level, relation between direct sound and early reflections, spectral characteristics of reverberation) had a significant effect on the tempo. A recent investigation conducted in an anechoic room and simulating different acoustical environments with a 6-channel loudspeaker reproduction [10, 11, 12] indicated that the playing tempo was not only reduced in very reverberant rooms but also under anechoic conditions. For some musicians, this also held for the loudness of their performances, but the results were less consistent there.

The findings of the studies mentioned call for further investigation by broadening the traditional scope on the relation of tempo, dynamics and reverberation and studying the influence of other room acoustical features on different aspects of music performance. Taking into account a longer musical context – most of the existing studies have concentrated on very short musical phrases only – as well as the individual performance concept of professional musicians might help to explain the current, partly conflicting findings.

To investigate the complex interaction of room acoustical conditions and performance characteristics under natural conditions, a field study was carried out with the cellist Jean-Guihen Queyras, one of the most renowned contemporary instrumental soloists. Seven performances of the six *Suites for Violoncello Solo* by Johann Sebastian Bach were recorded in different concert halls with a wide spec-

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Table I. Concert halls of the case study.

Concert hall	Abbreviation	Volume [m^3]	Stage [m^2]	Seats
Église du Collège St. Michel, Fribourg	ESM	9600	30	440
Cloître du Couvent des Cordeliers, Forcalquier	CCC	(open air)	39	480
Théâtre Jean Vilar, Vitry-Sur-Seine	TJV	11200	67	586
Gulbenkian Grande Auditorio, Lisboa	GGA	12600	108	1228
Auditorio Nacional Sala de Cámara, Madrid	ANC	5700	83	692
Cultuurcentrum, Hasselt	CCG	12700	101	812
Wigmore Hall, London	WMH	2800	32	542

trum of acoustical conditions (Table I). The extraction of performance features from the recordings as well as room acoustical measurements in the concert halls were the basis for a detailed analysis of the effect of room acoustic properties on music performance.

2. Methods

2.1. Recording and performance analysis

For the purpose of the investigation, the same musical programme had to be recorded in different acoustical surroundings. In five of the seven halls, all of the six cello suites by Bach were performed (6 x 6 movements = 36 pieces). In two halls, the programme consisted of other music pieces and parts of the Bach cycle (all 6 movements of suite no. 1 in ANC and first movement of suite no. 6 in CCC), which resulted in missing data for these cases.

For the musical recordings, a boundary microphone (Schoeps BLM 03 C) was placed at a distance of 11.5 cm in front of the cello spike, which was thus almost in the centre of the hemispherical directivity of the microphone (see Figure 1). Hence, even with an inclination of the instrument during the performances, the distance to the receiver remained constant and loudness fluctuations caused by instrument movements can be neglected. Moreover, due to the short distance between the microphone and the body of the cello and critical distances of 2.3 m to 7.1 m in the different halls, a level difference of 27 dB to 37 dB between direct and diffuse sound can be estimated. Therefore, the recordings were only marginally influenced by the sound of the halls.

When attempting to describe music performances on the basis of physical measurements such as recordings, a major difficulty lies in the identification of the most relevant aspects of music performance and the corresponding audio features. The latter problem is illustrated by the fact that the studies mentioned above already used a wide range of methods to quantify the loudness of a performance: vibration amplitude [8], MIDI velocity [9], and A-weighted SPL [12]. Attributes such as the basic tempo or the dynamics of a performance are at least as challenging to determine [13, 14]. The method for characterising the cello performances in this study was aimed at a perceptually meaningful analysis and is described below.

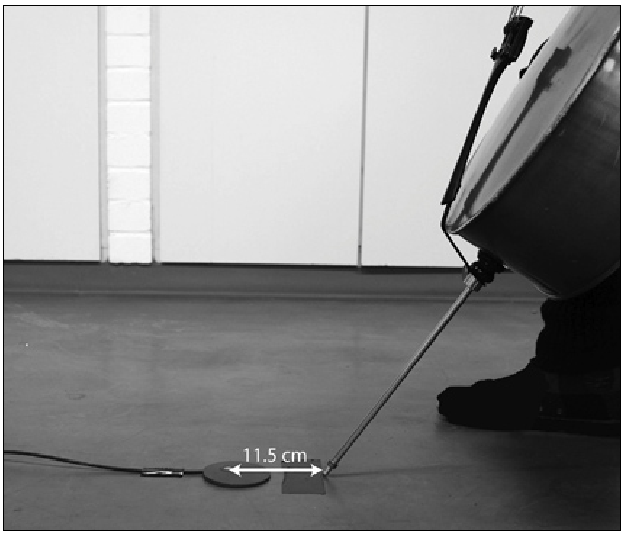

Figure 1. Recording setup with the boundary microphone at a distance of 11.5 cm in front of the cello spike.

From each of the 36 movements an excerpt was chosen for further analysis. Since all the movements of Bach's violoncello suites except the Préludes have a two-part structure, the first parts including their repetition were selected as excerpts, while a caesura of at least 22 bars after the beginning was chosen as breakpoint for the Préludes. This eventually resulted in 187 audio signals (5 rooms with 36 movements, 1 room with 6 movements, 1 room with 1 movement) with an average length of 54 s. Audio features were extracted from these recordings by means of a software-based analysis [15]: A dynamic time warping algorithm was used for the alignment of the input audio signal and a MIDI file representing the score, resulting in onset times for the played notes. The detected onsets were verified auditorily and corrected if necessary. A series of tempo observations in beats per minute was then calculated on beat and bar level on the basis of inter-onset and inter-bar intervals. Furthermore, seven loudness and nine timbre measures (see Table II; [16]) were calculated by the software for each musical event in the score.

The extracted audio features were used as components of regression models in order to predict perceptual qualities of musical performances, as shown in [17]. In that study, a first step comprised a panel discussion in which ten music experts defined a consensus vocabulary for qualities used to describe musical interpretations. This resulted in 16 qualities with corresponding bipolar attributes relating to different aspects of musical interpretation: temporal, dynamic and timbral aspects as well as overall impressions. Regarding these previously defined attributes, the same music experts then rated a total of 49 recorded performances, which were various interpretations of three different pieces (a Mozart piano sonata, a Beethoven string quartet and a Schubert cello sonata). At the same time, the technical features mentioned above were extracted from the 49 recordings. The experts' ratings were subsequently regressed on statistical measures for central tendency and dispersion determined for the time series of the extracted audio features. This resulted in a regression model for each performance attribute with 2 to 5 technically derived regression coefficients. To characterise the cello performances in the present study, only those regression models were used to describe the performance attributes that were predicted with more than 50% explained variance in [17]: 'Tempo', 'agogic', 'loudness', 'long-term dynamics', 'short-term dynamics', 'timbre (soft-hard)', 'timbre (dark-bright)', 'timbre (lean-full)' and 'timbral bandwidth'.

2.2. Room acoustical measurements and models

In order to determine the acoustical properties of the concert halls, measurements according to ISO 3382-1 [18] were conducted. An omni-directional source (Norsonic Nor276 with Nor280 Amplifier) was placed 1 m above the floor on stage at the position of the cello spike during the concerts, which was always in the centre of the stage. Impulse responses were measured at 1 m distance around the loudspeaker at a height of 1 m and, depending on the size and architectural structure of the halls, at 9 to 23 other receiver positions on stage and in the audience area at a height of 1.2 m. The receiver point on stage 1 m behind the loudspeaker facing the audience was defined as the musician's position, best representing the acoustical surrounding of the performer during the concerts. The other measurement positions were later used for validating room acoustical computer models (see below). Common room acoustical parameters and four stage measures (see appendix for definitions) were calculated from the impulse responses and frequency-averaged according to [18]: $EDT, RT, C_{80}, G, BR, ST_{\mathrm{early}}, ST_{\mathrm{late}}$ [19], $G_{\mathrm{e}}, G_{\mathrm{l}}$ [20]. The distribution of the frequency-averaged parameters in Table III represents the acoustical heterogeneity of the halls from the musician's perspective. Only G and G_{e} have a rather small range, due to the dominance of the direct sound at this short distance between source and receiver. The correlations between the frequency-averaged room acoustical measures at the musician's position are shown in Table IV.

It was crucial for the study to determine the acoustical situation during the concerts, but the measurements had to be conducted in unoccupied halls so they do not exactly reflect the concert conditions. Moreover, two of the concerts (in CCC and ESM) took place as part of festivals with temporary stages that were no longer available for the measurements. Therefore, computer models of the seven concert halls were generated with EASE 4.3 for further investigation of the concert conditions. CAD-plans provided by the hall management (in TJV, GGA, CCG), floor plans and in situ dimensional measurements were the basis for constructing the models shown in Figure 2. The scattering coefficients assigned to smooth surfaces in these models were set to rise from 0.05 to 0.70 between 1600 Hz and 2000 Hz, for more structured surfaces the slope of the curve was shifted towards lower frequencies [21]. The absorption coefficients of all the surfaces except the side walls in the models were set to typical values for the corresponding materials [22, 23, 24, 25, 26, 27]. The absorption values for both the auditorium and stage side walls were regarded as residual absorption and adjusted by fitting the octave bands of RT at the musician's position to the measurement data with an error smaller than the just noticeable difference (JND). The omni-directional source in the model was placed at a height of 1 m at the position of the cello spike, corresponding to the source in the real mea-

Table II. Loudness and timbre features extracted from the recordings. SR: Measure for signal bandwidth; SF: Simplified measure for roughness; SC: Gravity centre of spectral energy; SS: Measure for energy spread around SC; MFCCs: Components of the spectral envelope.

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

Table III. Mean, minimum and maximum of the frequency-averaged room acoustical parameters measured on the seven concert hall stages with 1 m distance between source and receiver (musician's position).

Parameter	Mean	Min.	Max.
EDT [s]	0.63	0.03	1.82
RT [s]	1.55	0.41	3.81
C_{80} [dB]	14.05	8.30	22.60
G [dB]	21.04	19.15	22.80
ST_{early} [dB]	−12.62	−18.17	−3.87
ST_{late} [dB]	−17.59	−25.08	−9.85
G_{e} [dB]	20.76	19.02	22.43
G_{l} [dB]	6.71	−0.97	13.15
BR [dB]	0.32	−1.96	4.55

Table IV. Pearson correlations between the frequency-averaged room acoustical parameters measured on the seven concert hall stages with 1 m distance between source and receiver (musician's position). *: $\alpha < 0.05$ (two-sided); **: $\alpha < 0.01$ (two-sided).

	EDT	RT	C_{80}	G	ST_{early}	ST_{late}	G_{e}	G_{l}	BR
RT	0.81*	1							
C_{80}	−0.78*	−0.55	1						
G	0.73	0.54	−0.22	1					
ST_{early}	0.51	0.10	−0.82*	0.00	1				
ST_{late}	0.69	0.43	−0.97**	0.14	0.88**	1			
G_{e}	0.60	0.48	−0.03	0.98**	−0.19	−0.53	1		
G_{l}	0.88*	0.63	−0.98**	0.41	0.75	0.93**	0.24	1	
BR	−0.07	−0.06	0.33	0.31	−0.18	−0.18	0.35	−0.25	1

surements. The described receiver position was chosen for the exact adjustment of the models because the acoustical conditions perceived by the performer were of special interest in the study. The spatial average of the other stage measurement positions served as a second control for the fitting procedure with errors not exceeding twice the JND. While RT was reproduced very well, this was not always possible for the support parameters and C_{80}, with errors of up to four times the JND. These measures are strongly dependent on early reflections, which cannot be reliably simulated if diffraction effects play a major role.

After fitting the models to the measurement data, stages were added in the models of CCC and ESM to restore the concert setups. In all of the models, the approximation of the concert situation was done in two steps. First, occupied audience areas corresponding to the size of the audiences during the concerts were inserted. To test the effect of this modification, simulated measurements were carried out, again with a receiver at the performer's position and an omni-directional source at the point of the cello spike, both 1 m above the floor. In a second simulation, a source with the directivity of a cello [28] was used to excite the room models. The acoustical centre of the instrument was defined at 0.4 m behind the spike and 0.6 m above the floor. In accordance with the documented distance between the cello spike and the cellist's head, the receiver was placed 0.4 m behind the source at the typical ear height of a seated person, 1.2 m. A comparison of these simulations with the data of the unoccupied computer models showed that for most of the calculated frequency-averaged room acoustical parameters the difference between the unoccupied and the occupied state of the halls was smaller than or in the range of the JND (see x's Figure 3). Only RT was noticeably affected by the presence of an audience, which corresponds to the findings in [29]. In contrast, the differences between the data of the occupied halls excited with the cello source and the unoccupied halls excited with an omni-directional source were greater than the JND for RT, the stage measures and C_{80} (see +'s Figure 3).

Since the differences between measurement and simulation were, for some parameters, in the order or higher than the differences due to the audience and the instrument's directivity, the acoustical parameters were not directly assumed from the simulation. Instead, the room acoustical parameters measured in the real halls at the performer's position were corrected by the (simulated) difference caused by cello and audience in all octave bands (+'s Figure 3). The statistical analysis described below was carried out with these corrected values.

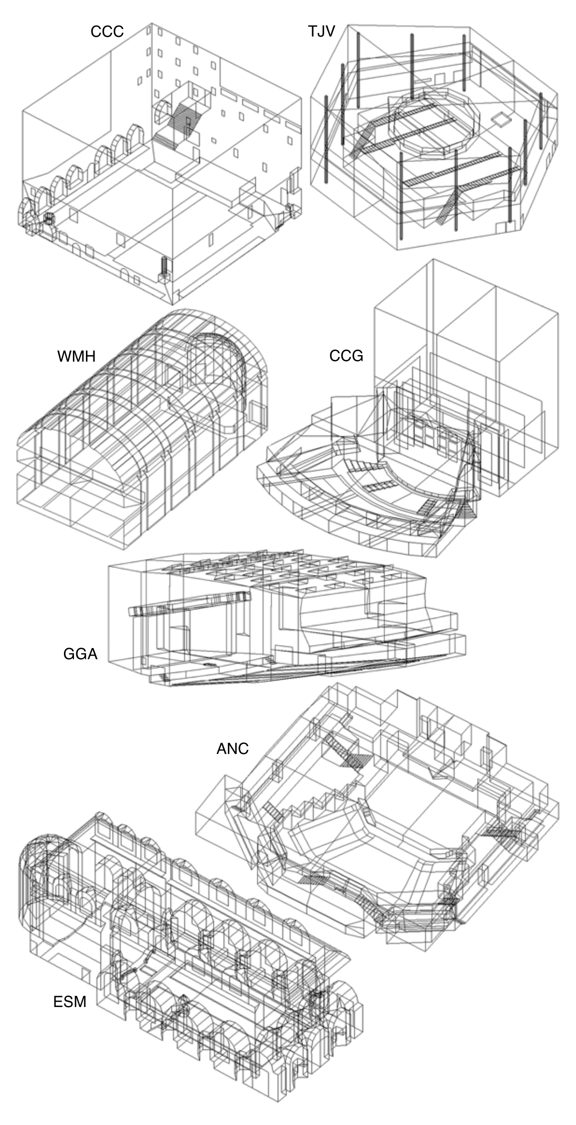

Figure 2. Room models.

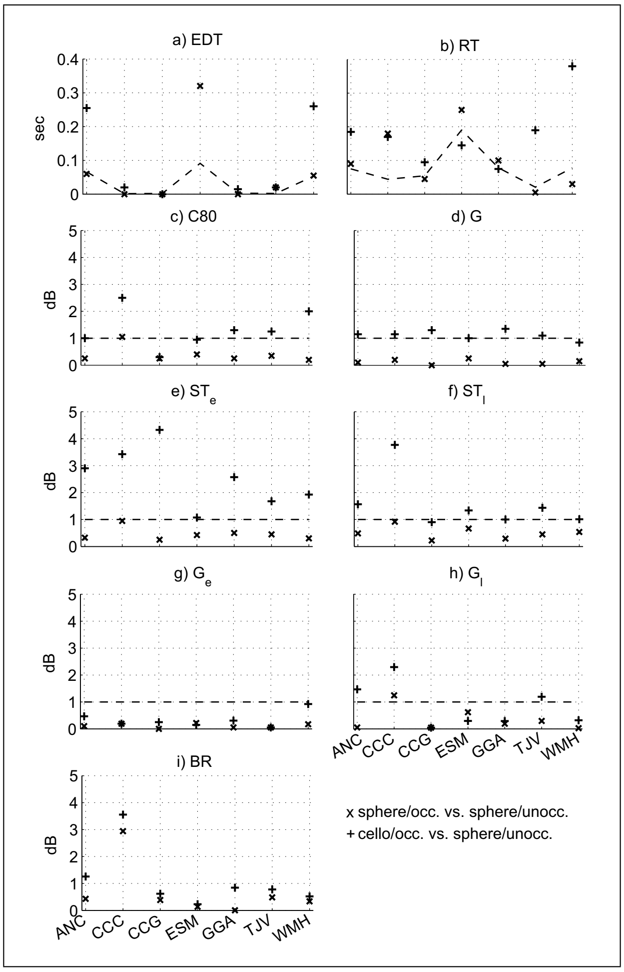

Figure 3. Frequency-averaged absolute differences between room acoustical parameters acquired in the computer models at the musician's position under different conditions: x's denote the difference between the unoccupied and the occupied rooms; +'s denote the difference between the unoccupied room excited with an omni-directional source and the occupied room excited with a cello source, i.e. the concert situation. The JNDs of the acoustical parameters according to [18] are shown as dashed lines.

2.3. Statistical Analysis

The aim of the statistical analysis was to reveal the influence of the nine room acoustical measures (independent variables) on the nine performance attributes (dependent variables) of the 36 pieces played in 7 concert halls. For this purpose, a multivariate hierarchical linear model (HLM) [30] with repeated measures on the piece level was employed. This method is similar to the common linear regression model, except that for data with a nested structure as encountered in this study, variances are considered on each level of the data (here: rooms and pieces). Since the portion of variance of the performance attributes induced by the pieces and by the room acoustics was estimated separately, the actual influence of the room acoustical parameters as regressors could be assessed more correctly than with a linear regression model.

However, the number of predictors in the model needed to be reduced because of the relatively few cases ($n =$ 7 halls) and the high correlations between the potential regressors (see Table IV). Hence, a principal component analysis (PCA) was performed with the room acoustical measures. 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, the PCA yielded four components that characterise 97% of the acoustical variance measured in the seven concert halls. The room acoustical parameters with the highest loading on each component were chosen as regressors for the HLM: RT, ST_{late}, G_{e}, BR. ST_{late} was used instead of the highly correlating ST_{early} measure (see Table IV), because according to ISO 3382-1 the latter describes ensemble conditions and was therefore expected to be less relevant for a solo performer. The PCA thus reveals four dimensions representing the room acoustical heterogeneity of the current set of performance venues and predicted by four room acoustical parameters. We suggest to interpret these as the perceived duration of reverberation (RT), the reverberant energy (ST_{late}), the early acoustical support (G_{e}), and the timbre of reverberation (BR). By choosing specific room acoustical parameters as predictors for the further analysis it was possible to explore the direct relationship between performance features and measurable parameters instead of interpreting the influence of complex PCA components. At the same time, the problem of multicollinearity between predictors in the HLM could be minimized by selecting only four salient parameters.

Table V. Loadings and explained variance for components resulting from a PCA with varimax rotation conducted with nine room acoustical parameters. The highest factor loadings are marked bold.

	1	2	3	4
ST_{early}	**0.96**	0.05	0.02	0.10
ST_{late}	0.87	−0.10	0.27	0.38
C_{80}	−0.81	0.05	−0.51	−0.17
G_{l}	0.76	0.22	0.53	0.19
G_{e}	−0.06	**0.98**	0.13	0.10
G	0.11	0.97	0.18	0.14
RT	0.22	0.20	**0.94**	0.00
EDT	0.64	0.37	0.65	0.00
BR	0.28	0.22	0.00	**0.93**
Expl. Var. [%]	38.81	24.39	21.97	12.34

To compare the proportion of variance in the data at room and piece level separately for each response variable v, intraclass correlation coefficients ρ_v were calculated for the performance attributes on the basis of the estimated room and piece level variances, $\sigma^2_{v|\mathrm{rooms}}$ and $\sigma^2_{v|\mathrm{pieces}}$, in intercept-only HLMs with no regressors,

$$\rho_v = \frac{\sigma^2_{v|\mathrm{rooms}}}{\sigma^2_{v|\mathrm{rooms}} + \sigma^2_{v|\mathrm{pieces}}}. \tag{1}$$

Since 'agogic' and 'timbre (lean-full)' were hardly varied across rooms compared to the variance across pieces (see Table VI) and the HLM was aimed at explaining only variance on the room level, it was problematic to include response variables with very little variance on this level. These two performance attributes with $\sigma^2_{v|\text{rooms}} < 0.1$, were thus excluded from the further analysis.

Consequently, the data was analysed with a multivariate HLM with seven performance features and four room acoustical predictors.

3. Results

Previous studies have found indications of an inverse quadratic relation between reverberation time and tempo [10], dynamics [8] and, at least for some musicians, loudness [10]. Considering all the possible combinations of RT and/or RT^2 as predictors for the seven response variables in the current study resulted in 128 possible models with the squared predictor being used between zero and seven times, while the other three room acoustical parameters were always entered as linear regressors. The most suitable relation (linear or squared) between RT and each performance feature was selected by comparing the proportion of explained variance on the room level [31] in each model,

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

n denotes the number of groups, i.e. rooms in the present case. $\sigma^2_{\text{M1}|\text{rest}}$ and $\sigma^2_{\text{M1}|\text{rooms}}$ are the residual variance and room level variance respectively in the target model (M1), while $\sigma^2_{\text{M0}|\text{rest}}$ and $\sigma^2_{\text{M0}|\text{rooms}}$ are the respective values in an intercept-only model with no predictors (M0). Based on the results of this comparison of 128 models, 'tempo', 'long-term dynamics' and the three timbre attributes were regressed on RT^2 whereas 'loudness' and 'short-term dynamics' were regressed on RT in the finally selected HLM. The explained variance of this model amounts to 58.27%. It should be considered that the pseudo-R^2 calculated here might be higher if some of the regressors were excluded from the prediction of some of the response variables. However, the purpose of the present analysis was to explore the extent of the effect of each room acoustical component on each performance attribute, rather than finding an individual, well fitted model. Taking into account that the response variables were measured in real-world concert situations with many other influencing factors, the pseudo-R^2 calculated here shows a very high explanatory power of room acoustical properties for the variance of performance attributes.

The parameters of the HLM were calculated with the restricted maximum likelihood method with standardised explanatory and response variables. The difference between the deviances of the intercept-only model (M0) and the full model (M1) was used in a chi-square test with degrees of freedom equal to the difference between the number of parameters in the two models. This so-called likelihood ratio test rejected the null-hypothesis ("the predictors have no effect") with $\chi^2_{28} = 260$ and $p < 0.01$.

Table VI. Variance on room and piece level and intraclass correlation coefficients for the nine response variables.

Response Variable	$\sigma^2_{v\|\text{rooms}}$	$\sigma^2_{v\|\text{pieces}}$	ρ_v
Tempo	0.52	0.45	**0.54**
Agogic	0.02	0.98	**0.02**
Loudness	0.10	0.94	**0.09**
Long-term dynamics	0.22	0.81	**0.21**
Short-term dynamics	0.33	0.74	**0.31**
Timbre (soft-hard)	0.68	0.30	**0.70**
Timbre (dark-bright)	0.69	0.25	**0.74**
Timbre (lean-full)	0.07	0.95	**0.07**
Timbral bandwidth	0.38	0.69	**0.35**

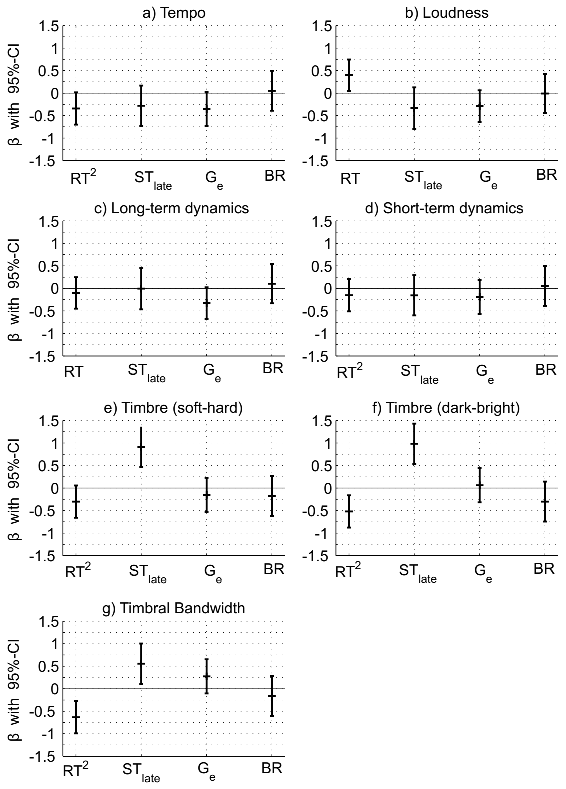

Figure 4. Standardised regression coefficients with 95% confidence intervals for the four room acoustical predictors (x-axes) and the seven performance attributes (a–g).

The standardised regression coefficients with 95% confidence intervals for each explanatory and response variable of the full HLM are given in Figure 4. They show the extent and the significance of the influence of the four room acoustical predictors on the studied performance attributes. Figure 5 depicts the regression curves for RT^2 resulting from the significant estimated coefficients. Since the explanatory variable plotted on the x-axes in Figure 5 is z-transformed, the zero point indicates its mean value.

Tempo As can be seen in Figure 4a, the playing tempo of the cellist was clearly influenced by the reverberation time, with both short and long reverberation times leading to slower tempi (see also Figure 5a). The fastest tempi

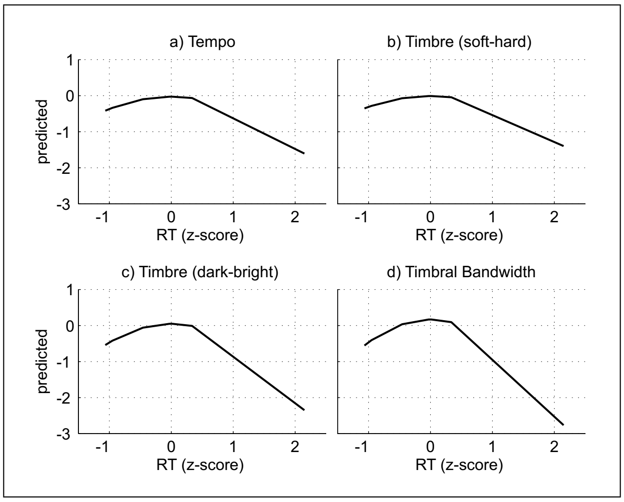

Figure 5. Regression curves resulting from the significant HLM parameters of RT^2 and the respective performance attributes.

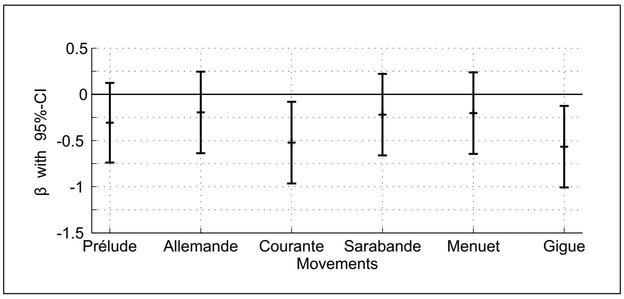

Figure 6. Standardised regression coefficients with 95% confidence intervals for RT^2 separately predicting the performed tempo of each movement type of Bach's cello suites.

were chosen under average conditions, with a mean reverberation time of the halls investigated of 1.55 s. Slowing down in reverberant environments is a response strategy frequently named by musicians; it was also mentioned by the cellist in the current study in guided interviews that were conducted after each concert. Also ST_{late}, indicating the perception of reverberant energy, tended to have a negative influence on the playing tempo. It appears intuitively plausible that a tempo reduction is necessary to avoid the excessive blurring of consecutive tones. The slowing down at very short reverberation times could, on the other hand, be the result of prolonging tones which are not carried by the reverberation of the room. G_{e} had a negative effect on the tempo, as well, suggesting that a decreasing level of very early reflections lead to a faster tempo.

Even though the 36 movements of Bach's suites for violoncello solo are each unique pieces, some of the six movement types are very similar across the six suites in terms of musical structure and character. One of the most obvious characteristics is the overall tempo, the Courantes and Gigues being fast movements while Allemandes and Sarabandes are slow movements. To test whether the effect of the room acoustical properties on the playing tempo was dependent on the character of the pieces, the movement type was entered as a factor into the HLM. The standardised regression coefficients with 95% confidence intervals for the prediction of 'tempo' with RT^2 are shown in figure 6 separately for each of the six movement types. The results demonstrate that the influence of the reverberation time tends to be higher in the fast movements than in the slower ones, confirming the finding in [12].

Loudness While previous studies suggested an inversely squared or negative linear relation between loudness and reverberation time [8, 9, 10], a more differentiated picture emerges from the current study. The performer tended to reduce his loudness with increasing early and late acoustical support, as predicted by G_{e} and ST_{late}. It seems immediately plausible to play softer in acoustically supportive environments. Increasing reverberation time, however, led to a significantly louder musical rendition. In one of the interviews after the concerts, the musician explained that he had learnt to respond to a lack of acoustical liveliness (also described as "not swimming in sound") with soft playing rather than forcing the sound of the instrument. With reference to the contrasting findings in previous studies, either the manner of adjusting the loudness in less reverberant acoustical environments is handled very individually among musicians or it might be a characteristic that distinguishes between experienced and inexperienced performers.

Dynamics Along with a reduction of absolute loudness with increasing early support G_{e}, the cellist also reduced the long-term dynamical bandwidth (Figure 4c). The short-term dynamics were not influenced significantly by any of the four room acoustical predictors.

Timbre The effects on two timbre attributes ('soft-hard' and 'dark-bright') are similar (Figures 4e and 4f), with ST_{late} having the greatest influence. An increasing perceived amount of reverberance obviously led to a harder and brighter tonal rendition, a playing technique described by the performer as "trenchant" and adopted in very diffuse environments. These timbre attributes might also be related to a more defined attack in articulation, which was mentioned by the cellist as a playing strategy in reverberant rooms, as well. The increase of hardness and brightness in timbre was accompanied by a higher overall timbral bandwidth which also increased with high reverberant energy. When comparing Figure 5a with Figures 5b-d, a similar influence of the reverberation time on the playing tempo and the timbre attributes can be observed. It is possible, that faster playing was partly accompanied by a brighter and harder timbre, maybe due to a more pronounced articulation.

4. Conclusions

This study investigated the effect of room acoustics on solo cello music performances under real-world concert conditions with a professional musician. Despite the many other factors present in such a performance situation, a clear and significant influence of different room acoustical conditions on the performance characteristics could be shown. A hierarchical linear model (HLM), accounting for the effect of four room acoustical parameters on seven performance features for (in total) 36 movements of the *Six Suites for Violoncello Solo* by Johann Sebastian Bach played in 7 concert halls, yielded an explained variance of more than 50%. Thus, more than half of the variance in performance features could be explained by the acoustical properties of the environment, whereas less than half of this variance may be attributed to other influencing factors such as audience, lighting, the visual impact of the environment or the current form and mood of the performer.

A detailed analysis of the influence of room acoustical parameters on different performance attributes showed that the playing tempo was mainly affected by the reverberation time, with a slower musical rendition for both very high and very low reverberation times. While the tempo seems to be reduced to avoid the blurring of consecutive notes through long reverberation tails, a prolongation of individual notes might replace the lack of reverberation under very dry conditions, also leading to slower tempi. Also, a strong early acoustical support led to significantly slower tempi. Furthermore, the effect of reverberation time on the overall tempo was stronger for the fast movements than for the slow movements of the suites.

Strong early and late acoustical support led to a reduced loudness of the performances, while the performer reacted with significantly increased loudness towards long reverberation times. This seems to be a convincing reason to clearly distinguish between the perception of reverberant energy (predicted by ST_{late}) and perceived duration of reverberation (predicted by RT). Both parameters were not only largely independent in the investigated sample of performance venues, but also had a contradictory effect on the musical rendition of the investigated performer.

A very strong influence was shown for all three timbral aspects under investigation. Late acoustical support (ST_{late}) as a predictor for perceived reverberant energy was strongly and significantly correlated to a brighter and harder timbral rendition and a larger overall timbral bandwidth. Surprisingly, no significant effect of the bass ratio on the timbral or any of the other performance features could be observed.

The results point out that the room acoustical conditions have a distinct impact on the way music is performed. Impressive quantitative evidence is provided by comparing the variation of performance features that can be explained by the musical pieces to the variation explained by different acoustical environments (see Table VI). While attributes such as the amount of tempo modulation ('agogic'), the absolute loudness and the dynamical bandwidth were almost completely determined by the requirements of the musical pieces, tempo and, in particular, timbral aspects were predominantly influenced by the acoustical environments, even for a selection of pieces as diverse as the different movements of the baroque suites investigated.

The question if the findings reported here hold for other performance situations and whether they are mainly due to the specific instrument or rather the individual performer cannot be answered on the basis of the current data. Future work will therefore include an experimental study with systematic variation of the test conditions, so the relations between room acoustical parameters and performance attributes can be investigated with different performers, different instruments and a varying musical repertoire.

Appendix

The stage parameters used in this study were calculated using the formulae [18, 20]

$$ST_{\text{early}} = 10\log_{10}\left(\frac{\int_{20\,\text{ms}}^{100\,\text{ms}} p^2(t)\,\mathrm{d}t}{\int_{0\,\text{ms}}^{10\,\text{ms}} p^2(t)\,\mathrm{d}t}\right) \tag{A1}$$

$$ST_{\text{late}} = 10\log_{10}\left(\frac{\int_{100\,\text{ms}}^{1000\,\text{ms}} p^2(t)\,\mathrm{d}t}{\int_{0\,\text{ms}}^{10\,\text{ms}} p^2(t)\,\mathrm{d}t}\right) \tag{A2}$$

$$G_{\text{e}} = 10\log_{10}\left(\frac{\int_{0\,\text{ms}}^{80\,\text{ms}} p^2(t)\,\mathrm{d}t}{\int_{0\,\text{ms}}^{\infty} p_{10}^2(t)\,\mathrm{d}t}\right) \tag{A3}$$

$$G_{\text{l}} = 10\log_{10}\left(\frac{\int_{80\,\text{ms}}^{\infty} p^2(t)\,\mathrm{d}t}{\int_{0\,\text{ms}}^{\infty} p_{10}^2(t)\,\mathrm{d}t}\right) \tag{A4}$$

$p(t)$ denotes the sound pressure at a specific receiver position, $p_{10}(t)$ is the sound pressure in the free field with the same sound source and at a distance of 10 m to the receiver, $t = 0$ is the instance of the impact of the direct sound.

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