Toronto, Canada
International Symposium on Room Acoustics
2013 June 9-11

Room acoustics viewed from the stage: Solo performers' adjustments to the acoustical environment

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ABSTRACT

When evaluating the acoustical quality of performance venues, the perspectives of the musicians and the audience need to be distinguished. Not only do their positions in the concert hall entail different acoustical transfer functions, also their involvement in the performance situation is not the same. This implies both a distinct access to the acoustical situation as well as potentially different requirements concerning the room acoustical conditions. While the perception of concert halls by listeners has been quite thoroughly studied and several parameters have been identified as appropriate predictors for their subjective impression, the perception of musicians turned out to be much more difficult to investigate. Most studies have used questionnaires to collect performers' responses to different stage configurations. In the study presented here, the immediate reaction of musicians to varying room acoustical conditions was investigated by analysing their performances. Solo instrumentalists were recorded while playing in a variety of acoustical environments simulated by dynamic binaural synthesis in an anechoic room. By means of a software-based analysis, performance-related audio features were extracted from the recordings. The effect of room acoustical properties on the performance properties was analysed with hierarchical linear models, revealing their relevance and their influence on the musical performances.

1 INTRODUCTION

Many room acoustical parameters have been studied and established to describe listeners' perception of auditoria,[1] whereas the identification of subjective qualities and corresponding physical parameters concerning the perception of musicians has not been similarly successful, so far. In seeking to pursue this question, the majority of studies used questionnaires for the evaluation of room acoustical conditions by musicians and correlated the subjective ratings with room acoustical parameters. This way, several technical parameters especially for the acoustics on stage have been proposed in the past three decades.[2,3,4,5,6] So far, only the support parameters (ST_{early}, ST_{late}) introduced as predictors for 'hearing each other' and 'reverberance' have been widely accepted and included into the ISO 3382-1[7] standard. However, later studies[8,9,10] found that a change of these perceptual qualities is not always accompanied by a change of the measured parameters. Moreover, it turned out that there are differences between solo, chamber and orchestra musicians concerning the perception of room acoustical attributes and the assessment of their relevance.[11,12,13,14]

Using questionnaires for the evaluation of room acoustics by musicians might entail problems because interpreters seem to have difficulties in distinguishing different perceptual acoustical qualities when asked to assess the acoustics of concert halls.[15] Moreover, the primary reaction of musicians to their room acoustical surrounding is rather their playing and not the verbalisation of their perception, which, by the way, is often characterised by a very diverse terminology. The current investigation therefore adopted a different approach by changing the perspective: Instead of interviewing musicians by means of questionnaires, their immediate reaction to room acoustical surroundings was investigated by focussing directly on their performances. The room acoustical conditions perceived by musicians are very likely to influence their way of playing, as it has been frequently described by scholars and interpreters. Thus, the knowledge of the parameters that have an effect on music performance can be viewed as evidence of their relevance for the room acoustical perception of musicians. Empirical evidence for the influence of room acoustics on music performance is rather sparse, but most of the existing investigations[16,17,18,19,20] indicated that reverberation had an influence on playing tempo and loudness. In a recent case study conducted with a professional cellist in real concert halls,[20] the loudness of the performances seemed to be mainly influenced by the early energy of the room, while RT and ST_{late} had a significant effect on timbral aspects of the cello performances. By including more performers and by controlling the variation of room acoustical conditions in a laboratory experiment, the study presented here was able to further contribute to these results. Computer models of 14 concert halls were auralised by means of dynamic binaural synthesis while two solo cellists were recorded performing the same music pieces in every hall. Based on the room acoustical parameters of the simulated rooms and on the extraction of performance features from the recordings, the influence and relevance of room acoustical conditions for music performances was studied in detail.

2 METHODS

2.1 Room acoustical models

The basis for the binaural simulations used in the experiment were computer models of 14 halls (see Table 1) generated with EASE 4.3 which covered a broad variation range of room acoustical parameters and whose architectural and structural properties were inspired by existing halls.[1,20,21,22] Three of the performance spaces were used in two versions (denoted as "a/b" in Table 1) with different absorption properties, i.e. reverberation times and frequency characteristics. For a comparison with the results of the above mentioned case study,[20] four of the performance spaces (shown in italics in Table 1) from that investigation were among the 14 halls of the experiment described here.

To determine the room acoustical properties of the concert halls, simulated measurements were carried out in each computer model. It was not the spatially averaged room acoustical characteristics that were of interest in this study, but rather the room acoustical parameters at the specific position of solo performers on stage. Both the omnidirectional source and receiver in the computer models were therefore placed 1 m above the stage floor and at a distance of 1 m, following the measurement procedure for the support parameters.[7] The receiver was thereby centred 2.5 m from the stage edge in every model. From the simulated measurements with this configuration, common room acoustical parameters and four stage measures were calculated: EDT, RT, C_{80}, G, BR, ST_{early}, ST_{late},7 G_{e}, G_{l}.[6] The mean, maximum and minimum of the frequency-averaged parameters are listed in Table 2, showing the large acoustical variety of the performance spaces. Only G and G_{e} show quite a small range of variation, which can be assigned to the dominance of direct sound at this short distance between source and receiver.

Table 1: Features of the computer room models used in the experiment. The affix “a/b” denotes the halls generated with two different versions of absorption properties; the numbers printed in italics denote virtual environments corresponding to concert venues used in a previous study.[20]

Nr.	Purpose	Shape / Audience area	Stage	Volume [m^3]	Stage size [m^2]
1	Chamber hall	Rectangle / plane	Enclosed	2335	56
2 a/b	Chamber hall	Rectangle / plane	Enclosed	3233	85
3 a/b	Concert hall	Hexagon / vineyard	Exposed, in hall centre	21661	109
4	Concert hall	Rectangle / plane	Exposed	10261	186
5 a/b	Baroque church	Rectangle / plane	Exposed, before apse	12530	55
6	Opera	Semicircle / inclined	Exposed, before curtain	14862	97
7	Chamber hall	Square / vineyard	Exposed	5714	83
8	Concert hall	Rectangle / inclined	Exposed	12553	108
9	Theatre	Hexagon / inclined	Exposed, before fire curtain	11175	67
10	Chamber hall	Rectangle / plane	Exposed, before apse	2773	32
11	Historical concert hall	Rectangle / plane	Exposed	900	29

Table 2: Mean, minimum and maximum of frequency-averaged room acoustical parameters measured on stage with 1 m distance between source and receiver

Parameter	Mean	Minimum	Maximum
EDT [s]	0.38	0.04	1.24
RT [s]	1.63	0.60	3.14
C_{80} [dB]	13.40	7.40	19.10
G [dB]	21.23	20.25	22.55
BR [dB]	0.70	-2.78	3.12
ST_early [dB]	-11.10	-19.30	-5.55
ST_late [dB]	-16.67	-21.94	-9.69
G_e [dB]	20.97	20.17	21.86
G_l [dB]	7.57	1.50	14.42

2.2 Generating BRIR datasets

In order to simulate the instrument specific excitation of the performance spaces for the auralisation of the computer models, the directivity of the sound source in the models was adapted to a cello by using a dataset of source models of orchestral instruments.[24,25] The BRIR datasets needed for the dynamic binaural simulations were generated in four steps: First, a reflectogram was produced in each model, recording the angle of impact, the arrival time as well as the sound level in third octave bands from 100 Hz to 10 kHz of every reflection at the receiver position. This receiver position was 2.5 m behind the stage edge and 1.2 m above the floor, simulating the typical ear height of a seated person. The source location for the reflectogram was defined by assuming the acoustical centre of a cello at 0.6 m above the floor and 0.4 m in front of the receiver position. In the next step, impulse responses were generated for each reflection of the reflectogram by interpolating between the third octave bands and extrapolating above and below the highest and lowest bands and by reconstructing a minimum phase for each spectrum. The third step consisted of convolving these impulse responses with head related transfer functions[23] corresponding to the angle of impact stored for each reflection of the reflectogram. Finally, the convolution results were added up taking into account of the arrival time of the reflections, thus yielding a complete binaural room impulse response (BRIR). The direct sound was not included in this procedure, as it was only the response of the rooms and not the source itself that needed to be simulated in the experiment. This BRIR generation procedure was repeated for head rotations of ±50° and head elevations of -30° to 21° with a resolution of 2° and 3°, respectively,[26] resulting in a dataset of 918 BRIRs for each room model.

2.3 Auralisation and experimental procedure

The experiment took place in an anechoic chamber and was conducted with two professional solo performers. The auralisation of the performance spaces using the BRIR datasets described above was realised with a system for dynamic binaural synthesis that enables a highly plausible sound field simulation.[27] The head movements of the musician were detected by a head tracker (Polhemus PATRIOT) and the dry sound signal recorded with a microphone (Sennheiser MKE 1) attached to the instrument was convolved in real-time with the BRIR matching the respective head position. The simulation of the room response excluding the direct sound was presented over extra-aural headphones (AKG K1000) allowing for an unimpeded path of the instrument's direct sound to the performer's ears. The frequency responses of both the recording and the playback device were compensated, whereby the headphones were equalised individually for each musician.[28]

Figure 1: Cellist wearing extra-aural headphones playing in one of the virtual rooms with a microphone attached to his instrument.

The performers attended the experiment in two sessions with seven rooms each. Before the actual experiment, the measurement of the individual headphone transfer function needed for the headphone compensation was carried out. Additionally, a loudness calibration of the simulation was necessary, because while the intra-room loudness was correct due to an identical sound level of the sources in all of the computer models, the proper loudness of the simulations relative to the direct sound needed to be determined. This was achieved in the following procedure: First, a single tone played by the musician was recorded with both the instrument microphone and a dummy head (Neumann KU 81i) at 5 m distance. Then, the headphones were placed on the dummy head and the tone previously recorded at the instrument was played through a binaural simulation of an anechoic chamber, generated with a source-receiver distance of 5 m. This simulation was again recorded with the dummy head so that the RMS of both dummy head recordings yielded the correct scaling factor for the binaural simulations of the concert halls. During the actual experiment, the performer was given 10 minutes to become accustomed to each virtual room. Then, he was recorded while playing excerpts of two music pieces of his choice lasting approximately one minute each and differing in their basic tempo. Additionally, the pieces provided variations in dynamics, articulation and range. The warm-up and the recording of the same two pieces was repeated in each of the randomly presented virtual rooms.

2.4 Performance analysis and statistical analysis

It has been shown that describing the qualities of musical performances by means of acoustical properties derived from recordings is not a trivial task.[29,30] The aspects of music performance investigated here were based on a consensus vocabulary of attributes for the description of musical interpretations defined by music experts:[31] ‘Tempo’, ‘agogic’, ‘loudness’, ‘dynamical bandwidth’, ‘timbre (soft-hard)’, ‘timbre (dark-bright)’ and ‘timbre (lean-full)’. The method to describe these attributes by means of signal-based features is described in the following and followed the same procedure as the study by Weinzierl et al.:[31] The basis for the analysis were the recordings of two cellists each playing excerpts of two movements from the *Suites for Violoncello Solo* by J. S. Bach (Gigue and Sarabande of suite no. 5; Prélude and Sarabande of suite no. 1) in 14 rooms, resulting in 56 audio signals with an average length of 76 s. By means of a software-based analysis,[32] audio features were extracted from these recordings: The onset times of the played notes were detected by aligning the audio signal to a MIDI file representing the score. The detected onsets were verified auditorily and corrected if necessary and the tempo of each musical event was calculated. Furthermore, time series of five loudness and nine timbre measures were extracted by the software. Following Weinzierl et al.[31], statistical measures of central tendency and dispersion were calculated from the time series of the extracted features and standardised (z-score) within each music piece. These measures were used as coefficients in regression models determined in a listening test[31] to predict the seven qualities of music performances mentioned above.

The purpose of the statistical analysis was to investigate the influence of the room acoustical parameters (independent variables) on the performance attributes (dependent variables) of four pieces played by two musicians in 14 rooms. The data clearly show a nested structure with three levels (rooms, musicians, pieces), so a hierarchical linear model (HLM)[33] was employed for the analysis. This method is similar to the common regression analysis, but variances are estimated separately on each level of the data and the coefficients are thus estimated more correctly. In order to reduce the number of possible predictors in the model, a principal component analysis (PCA) was conducted with the room acoustical parameters. The criterion for the number of extracted components was set to a minimum of 95 % of cumulative proportion of explained variance. After varimax rotation, the PCA yielded four components characterizing 97.5 % of the acoustical variance (Table 3). The room acoustical parameters with the highest loading on each component were EDT, RT, G_e and BR. While the latter three parameters are identical to the ones used as room acoustical predictors in the case study mentioned above,[20] it was ST_{late} that was used that investigation instead of EDT. Considering that ST_{late} showed an only slightly lower loading on the first component (see Table 3), EDT was replaced by ST_{late} as a room acoustical predictor for the further analysis presented here for a better comparison of the results of the two studies. Since strong empirical evidence has been found for a quadratic relationship between the reverberation time and ‘tempo’[19 20] as well as ‘timbre (soft-hard)’ and ‘timbre (dark-bright)’,[20] *RT* was used as a quadratic predictor for these performance attributes just as in the case study.

Table 3: Components resulting from a PCA with varimax rotation conducted with the room acoustical parameters measured in the room models. Highest loadings are marked bold.

	Components			
	1	**2**	**3**	**4**
EDT [s]	**0.897**	0.251	-0.124	0.260
C_{80} [dB]	-0.884	-0.373	-0.227	-0.136
ST_{late} [dB]	0.875	0.437	-0.036	0.156
G_{l} [dB]	0.857	0.444	0.204	0.138
ST_{early} [dB]	0.680	0.649	-0.091	0.033
G_{e} [dB]	0.369	**0.917**	-0.051	0.118
G [dB]	0.582	0.786	-0.009	0.158
RT [s]	0.049	-0.051	**0.995**	-0.015
BR [dB]	0.210	0.118	-0.012	**0.969**
Expl. Variance	45.21 %	27.64 %	12.34 %	12.31 %

3 RESULTS

In the case study with the cellist recorded in real-world concert situations,[20] it was shown that the effect of some of the room acoustical predictors was dependent on the musical content. For a further investigation of this evidence, the factor ‘piece type’ with the values ‘fast’ (for the Gigue and the Prélude) and ‘slow’ (for the two Sarabandes) was entered into the HLM (M1) in the current study. Even if the movements played by the cellists are all musically unique, their tempo characteristic was considered to be similar enough for this classification. The parameters of the HLM were calculated with the restricted maximum likelihood method and with standardised dependent and independent variables. The resulting regression coefficients showed that the difference between the two piece types was not evident for all interrelations between room acoustical predictors and performance attributes. Therefore, a second model (M2) was calculated, using the factor ‘piece type’ only for those interrelations where the 95 % confidence intervals (CI) for the slow and the fast pieces in model M1 did not overlap (indicating a significant difference for different piece types). A further question to be considered when investigating the reaction of more than one musician to room acoustical conditions is whether there are differences in the individual response strategies of the performers. To examine this, the same method was employed as described for the factor ‘piece type’: First, a model M3 with the factor ‘musician’ for all interrelations between regressors and response variables was calculated (factor ‘piece type’ as in M2). Then, in the final model M4, the factor ‘musician’ was used only for those interrelations where the two musicians reacted significantly different (CI not overlapping). The regression coefficients along with 95 % CI of this model M4 are depicted in Figure 2 and show the extent and significance of the effect of each room acoustical predictor on each performance attribute that was investigated. As explained, some of the effects are further differentiated concerning the factors ‘piece type’ or ‘musician’. Given the relatively few data points, it is not surprising that some of the coefficients are not significant, but clear tendencies can nevertheless be observed. For a direct comparison, the results of the case study are shown in Figure 3 (the performance aspects ‘agogic’ and ‘timbre (lean-full)’ were not investigated there).

Perhaps the most striking result is the effect of the reverberation time on the playing tempo. In the case study, an inversely U-shaped relationship was observed, indicating a slower tempo both for very reverberant and very dry conditions (Figure 3a). In the laboratory study, this was confirmed only for the slow pieces, whereas the fast pieces were played significantly faster in rooms with long and very short *RT* (Figure 2a, grey vs. black).

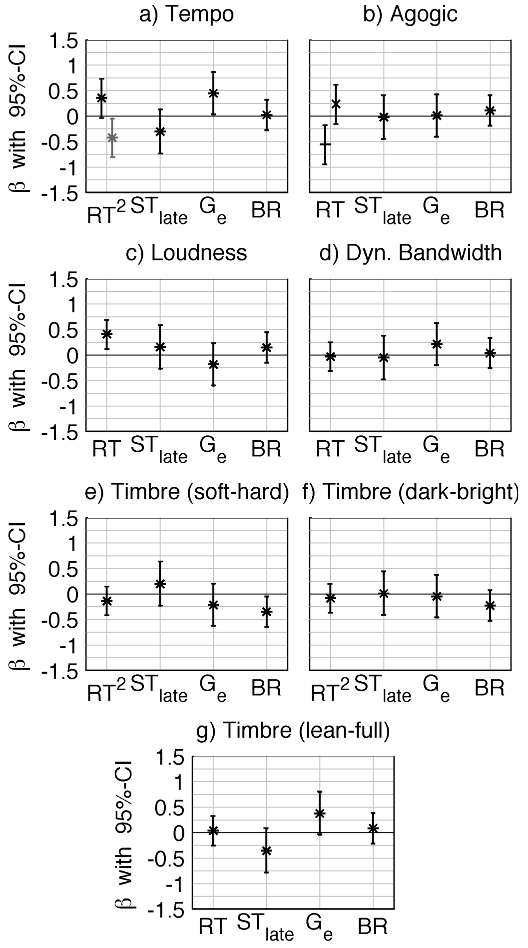

Figure 2: Standardised regression coefficients with 95 % CIs for each room acoustical predictor (x-axes) and performance attribute (a – h). Black: fast piece/both pieces; grey: slow piece; –: musician 1; x: musician 2; *: both musicians

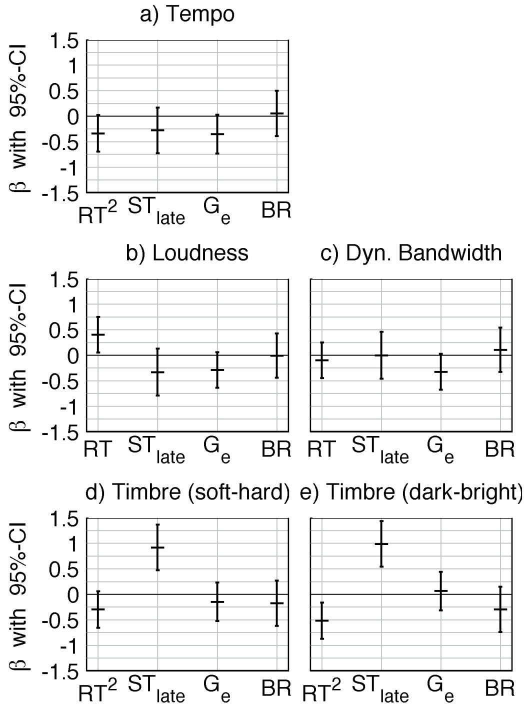

Figure 3: Results from a case study with a cellist playing in real concert halls.[20] Standardised regression coefficients with 95 % CIs for each room acoustical predictor (x-axes) and performance attribute (a – e).

These results correspond to statements the cellists made in guided interviews conducted after the recordings in each virtual room: The first performer indicated that she tried to play the fast piece very short in very reverberant rooms to achieve a better clarity, supposing that this also led to faster tempi. In contrast, she explained to play the Sarabande slower as a reaction to long *RT*. The second cellist, although indicating that he did not consciously adapt his playing technique to the room acoustical conditions, mentioned that he played the Sarabande faster in rooms with rather short *RT*. As Figure 2a shows, the early acoustical support, G_e, also had a significant effect on the playing tempo in the laboratory study with no large differences between piece types and musicians. This was also observed in the case study but, interestingly, with the opposite relation (Figure 3a).

There is a significant difference between the two cellists of the laboratory study concerning the effect of *RT* on ‘agogic’, i.e. the extent of tempo modulations during the performance (Figure 2b, - vs. x). While the first musician seems to have restricted this modulation bandwidth with longer *RT*, the other performer indicated that because of the positive atmosphere created by long reverberation times, he tended to use more tempo variation under such conditions, which can indeed be observed in Figure 2b.

Under laboratory conditions, the influence of *RT* on the loudness of both musicians in both piece types was not very large but highly significant (Figure 2c). The same result was found under real-world conditions (Figure 3b), where the cellist explained that he had learnt to play more *piano* in acoustically dry environments instead of forcing the sound. The reaction of playing softer in rooms with high G_e, which seems to be a plausible reaction to acoustical enhancement, was found as a tendency both in the case study (Figure 3b) and under laboratory conditions (Figure 2c).

The dynamical bandwidth was not significantly influenced by any of the room acoustical parameters, neither for the musicians in the laboratory study (Figure 2d) nor for the musician recorded in real concert situations (Figure 3c).

The first two timbre attributes (‘soft-hard’, ‘dark-bright’, Figure 2e and 2f) were both similarly influenced by *BR* in the laboratory study: A high bass ratio led to darker and significantly softer playing in both pieces and for both musicians. A tendency of this reaction can also be seen in Figure 3d. Obviously, none of the performers used the timbre of their instrument to *compensate* for the spectral properties represented by the bass ratio of the concert halls encountered. A tendency to play harder in rooms with high late energy and softer in rooms with high early energy can be observed in Figure 2e. Both effects are in line with the results of the case study (Figure 3d), the latter one possibly due to the notion to play not only softer in loudness but also in timbre in acoustically supportive environments (see Figure 2c and 2e). A strong tendency of ST_late and G_e on ‘timbre (lean-full)’ for both musicians and piece types was observed in the laboratory study: A lean timbre was used in the presence of strong reverberant energy, while the opposite was the case in conditions with high early energy.

4 CONCLUSIONS

When it comes to the evaluation of room acoustical surroundings by musicians, it is still largely unclear which perceptual qualities and which corresponding physical parameters are relevant for the performers. Instead of using the traditional approach of a questionnaire study, the investigation presented here observed musicians’ responses to room acoustics by focusing directly on their way of playing. A laboratory study with simulated concert spaces based on room acoustical models was conducted by recording the performances of two professional solo cellists in the virtual halls. The results were compared to the findings of a previous case study conducted with a cellist under real-world concert conditions.

The statistical analysis by means of a hierarchical linear model showed a clear influence of all four room acoustical parameters that represent four dimensions of the room acoustical heterogeneity of the studied concert spaces from the perspective of a musician. The reverberation time (*RT*) had an influence on the tempo, the extent of tempo variations (‘agogic’), and the absolute loudness. The effects of reverberant energy (ST_late), early acoustical support (G_e) and the bass ratio (*BR*) became apparent on different features for the tonal rendition of the cello players (‘timbre (soft-hard)’, ‘timbre (dark-bright)’ and ‘timbre (lean-full)’). These effects can be taken as evidence for the relevance not only of the support parameters often used to describe stage acoustics, but also of parameters related to the late part of the impulse response, such as *RT* and *BR*.

Both under laboratory conditions and in the concert situation, there was a significant interaction between reverberation time and tempo. However, the specific influence on tempo as well as tempo modulation was dependent both on the properties of the musical piece performed and the individual performance strategy of the musicians observed. Thus, the use of tempo and timing not only seems to be the predominant strategy constituting the specific interpretation of an individual piece by an individual musician;[34] the adaption of tempo and timing towards different acoustical conditions seems to be similarly individual. This could explain why it turned out to be difficult to find simple and systematic correlations in previous studies.[17,18] The adaption of the dynamical and timbral musical rendition, on the other hand, seems to be more homogenous across performers and musical content. Strong early acoustical support, represented by G_e, induced the performers to play softer both in absolute loudness and in timbre. Late reverberant energy, represented by ST_{late}, on the other hand, seems to trigger a ‘harder’ rendition, probably due to a more pronounced articulation.

The significant effects observed along with several strong tendencies support the assumption that studying the performances of musicians instead of letting them evaluate questionnaires provides an immediate approach not only to their perception but also to their acoustically influenced behaviour. Apparently, the observed adaption of the performance to room acoustical properties is not always conscious, as the musician who indicated that he would not adapt his way of playing to the acoustical environment yielded a similarly strong response to the room acoustical predictors as his colleague.

In future work, the question in how far response strategies generally vary among musicians or whether certain aspects are typical for certain musical instruments will be investigated by taking into account different instrument types along with their individual performers. In addition, more room acoustical parameters will be studied in order to explore their importance for music performance.

ACKNOWLEDGMENTS

The authors wish to thank the musicians who took part in the experiment for their collaboration. This work was funded by the German National Academic Foundation.

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