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HOW SINGERS ADAPT TO ROOM ACOUSTICAL CONDITIONS

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1 INTRODUCTION

The perception of musical performers with regard to their acoustical environment, which has received increasing attention since the late 1980s[1, 2], is different from the perception on the part of the audience. The motor activity of the musician, which absorbs much of his attention, the proximity of his instrument and other instruments as sound source(s), as well as the need to hear him- or herself and other ensemble players sufficiently well for a high quality performance can entail substantially different needs and expectations towards the room acoustical conditions on stage.

Recent research has also addressed the question, to what extent and in which way not only the perception but also the way of playing of musical performers depends on the acoustical environment[3-5]. In one of these studies, musicians were exposed to different acoustical environments simulated by a multichannel loudspeaker system in an anechoic chamber. As a result, significant differences in terms of tempo, vibrato, and sound level were observed under the different acoustical conditions[6]. A comparison of features extracted from the audio signal with the response of the musicians given in questionnaires filled out after the recording indicated that many of the adaptations of the interpretation style were made consciously, such as a more pronounced staccato and longer pauses between notes with increasing reverberation time[7].

Another study[8] has been carried out in seven real halls in which a cellist played the same musical program during a concert tour. Room acoustical measurements were performed in the empty rooms, and computer simulations were conducted to estimate the acoustics in the occupied condition. The musical recordings were analyzed in terms of tempo, dynamics, loudness, and timbre characteristics. A statistical analysis of the relationship between room acoustical parameters according to ISO-3382-1[9] and audio features representing qualities of the musical performance revealed that more than 50% of the variance in performance features could be explained by the acoustical properties of the environment. With a similar test design, the same authors invited 12 musical performers playing six musical instruments to perform the same pieces of music in different acoustical conditions, simulated by dynamic binaural synthesis, thus avoiding the confusion with other influencing factors such as the visual impression, audience reactions, or the design of the stage[10]. The statistical analysis again revealed a significant influence of room acoustical parameters on the way of playing, but also very *individual* patterns of reaction, which strongly varied not only between different musical instruments but also between different performers on the same instrument.

The interaction of singers with their room acoustical environment was investigated mainly in the context of choir performance. Marshall and Meyer placed an ensemble of singers in a semi-anechoic room, where they were exposed to synthetic sound fields including discrete reflections arriving from the side and rear, combined with an artificial reverberation tail[11]. The experiment demonstrated the strong influence of reverberation on the comfort of singers. Early reflections were appreciated if their time delay did not exceed 40 ms, beyond which they became unpleasant. A more recent work[12] focused on the effect of early reflections when singing in small ensembles (2 to 4 singers) in a church. Artificial early reflections were added to the natural acoustics of the venue by means of microphones and loudspeakers. The different groups of singers performed musical pieces with various tempi and as a result, it appeared that singing in fast musical tempi benefits from strong early reflections whereas they do not significantly impact slow-tempo singing.

These results complement well with the work of Ternström[13], who analysed the performance of three choirs in three different rooms, and demonstrated the influence of room acoustics both on the long-time average spectrum (LTAS) and the sound power produced by the singers[14]. The way a singer or a speaker adapts his voice production during a performance or a communicative situation in general strongly depends on the auditory feedback the singer or speaker has from his own voice. As a measure for this, Ternström introduced the self-to-other ratio that accounts for the sound level difference between a singer's voice and his surrounding environment, including other singers in choir and sound reverberation in the room[15]. More recent studies have shown that auditory feedback affects not only the power, but also the quality and the pitch accuracy of singers, with the loudness decreasing and voice quality (singing power ratio, SPR) and the pitch accuracy increasing with the degree of auditory feedback[16, 17].

Previous investigations have thus been mainly focused on the interaction between instrumentalists and room acoustical conditions, while the singing voice was mainly considered in the context of how choir performance is related to room acoustical qualities[18]. The adaptation of solo singers to the room acoustical conditions, however, has not been investigated in detail. Following the methodology of a previous study[8] conducted at TU Berlin, the present work investigates, to what extent and in which way the performance of singers (as described by features of the audio signal) is related to properties of the performance space (as described by room acoustical parameters). For this purpose, we have invited 4 solo singers to perform an identical repertoire in 6 different rooms covering a wide range or room acoustical conditions. In the following, the measurement approach towards the properties of the rooms and the musical performance is described, as well as a statistical analysis of the interrelation of the two domains.

2 METHODS

2.1 Room acoustics measurements

Stage acoustical measurements were carried out in each of the 6 rooms, documenting a broad range or acoustical characteristics in the selected sample of rooms for the current study (Tab. 1). A system of heavy banners could be deployed in two of these rooms, leading to a considerable change of most acoustical parameters beyond their just noticeable threshold (JND)[19, 20], and resulting in 8 different acoustical environments for the singers. The rooms include a symphonic concert hall (Philharmonie Berlin), a church of medium size (St Eduard Church) a cabaret theater (Distel), a recording studio, a small (Kammersaal) and a medium size chamber music hall (Joseph Joachim Saal), the last three being used by the Berlin University of the Arts (UdK). The measurements were performed by means of a dodecahedron speaker (Norsonic Nor276 and amplifier Nor280) generating logarithmic sine sweeps (3 sec, 20 Hz-20 kHz) and placed on stage at the usual position of a solo singer. A class-1 measurement microphone (NTi Audio M2230) was placed 1 m away from the acoustical center of the source in its horizontal plane. The interaural cross correlation (IACC) was measured on stage by means of a dummy head (Neumann KU100) and a small broadband speaker (Fostex 6301B) with a directivity close to the human voice, and placed just before the mouth of the head.

2.2 Musical recordings

In each room, the 4 solo singers involved in this study were invited to sing a musical program, including excerpts of three musical pieces with various tempo and dynamics. The characteristics of the singers and musical pieces are shown in Tab. 2. Recordings were done with a miniature omnidirectional microphone (DPA 4060) positioned 3 cm away from the singer's mouth edge, with an external audio interface (RME Fireface UFX) allowing to capture the voice signal with a very low level of reverberation.

Room name	Volume (m^3)	T_{30} (s)	EDT (s)	C_{80} (dB)	G_{late} (dB)	IACC
Recording studio (w/o banners)	420	0.8	0.7	9.2	12.2	0.70
Recording studio (w/ banners)	420	0.6	0.5	12.8	8.2	0.73
Kammersaal	590	1.1	1.0	7.2	13.8	0.72
Cabaret theater Distel	1700	0.7	0.5	11.6	8.5	0.76
Joseph Joachim Saal (w/o banners)	3660	2.2	1.8	3.4	10.8	0.76
Joseph Joachim Saal (w/ banners)	3660	1.5	1.3	7.4	8.9	0.76
St Eduard Church	9360	5.0	4.3	0.3	14.0	0.53
Philharmonie Berlin	22000	2.0	1.2	7.6	3.8	0.73

Table 1 – Main parameters of the rooms measured on stage, averaged over the 500 Hz and the 1 kHz octave bands, except for IACC: 125 Hz to 4 kHz octave bands, according to ISO3382-1[9].

2.3 Room acoustic parameters

Based on the measured impulse responses from both the omnidirectional microphone and the dummy head, standard room acoustical parameters were calculated according to ISO 3382-1[9]. To analyse the interrelation of room acoustical conditions and performance qualities, four parameters were selected which represent the most important perceptual properties of the room[21] and which were shown to be largely independent of each other in earlier studies[8, 10]. These include the early decay time (EDT) as a good predictor of the perceived reverberance[22], $IACC_{early}$ as a measure of the perceived source width[23], G_{late} as a relevant estimation of the subjective level of late sound[2], and the bass ratio (BR) as a measure of the perception of the tonal color of the room[24]. The indices *early* and *late* correspond to time intervals before and after 80 ms respectively. The parameters were calculated using the ITA Toolbox[25] (T_{30}, EDT, C_{80}) and custom made codes based on the ISO3382-1[9] standard (G_{late}, IACC) and related publications (G_{late}[2], $IACC_{early}$, and BR[23]).

Voice type	Age	Chosen musical pieces	Pace
Soprano	23	Mozart – Ach ich liebte (Aria from Entführung aus dem Serail)	Fast
		Puccini – Aria from Manon Lescaut	Medium
		Verdi – Aria from Rigoletto	Slow
Mezzo soprano	27	Schubert – Nur wer die Sehnsucht kennt	Slow
		Bach – Esurientes implevit bonis (Aria from Magnificat)	Medium
		Mozart – Aria from Le nozze di Figaro	Fast
Tenor	21	Schubert – Ganymed	Medium
		Cesti – Intorno all idol mio	Slow
		Händel – Aria from Tamerlano	Fast
Baritone	26	Fauré – Au cimetière	Slow
		Händel – Honor and arms (Aria from Samson)	Fast
		Humperdinck – Aria from Hänsel und Gretel	Medium

Table 2 – Singers and musical pieces

2.4 Musical descriptors

Following the aim of determining correlations between room acoustics and musical behavior, it is necessary to compare the room acoustical parameters to musical features extracted from the recordings of each singer in each room. Therefore, each recorded note had to be analyzed in order to estimate a number of musical features which could describe a given performance and make it objectively comparable. The first step was to detect the onset of each note. This was performed by a program[26] previously developed at TU Berlin, which compares a MIDI score with the corresponding recording by means of a dynamic time warping algorithm. The obtained onsets must be manually corrected because onset detection algorithms still present a certain rate of mistakes, especially when dealing with *a capella* singing[27]. This correction was based on visual inspection with the SonicVisualiser[28] software. The second step is the estimation, between two consecutive onsets, of the musical features as commonly performed in the music information retrieval (MIR) community. A collection of 4 features was generated, related to tempo at bar level, loudness as defined by Zwicker[29], timbre brightness, and dynamics rate as presented in Tab. 3.

Room acoustical parameters			**Musical descriptors**		
Name	**Group**	**Description**	**Name**	**Group**	**Description**
EDT	Time	Room reverberance	Bar	Tempo	Tempo at bar level
G_{late}	Strength	Late acoustical support	Z2	Loudness	Zwicker's Loudness
$IACC_{early}$	Spatiality	Apparent source width	SC	Timbre	Spectral centroid, brightness
BR	Timbre	Tonal color of the room	SF	Timbre	Spectral flux, dynamics rate

Table 3 – The selected parameters used for the statistical analysis

2.5 Statistical analysis

To analyse the interrelation of room acoustical parameters and features of the musical performance, the latter variables were z-transformed, according to

$$Xz = \frac{X - mean(X)}{std(X)} \quad , \tag{1}$$

with *mean* and *std* as the arithmetic mean and standard deviation of the series *X*, thus avoiding the influence of the units and the scaling of each variable, only retaining the influence of their relative variation. All possible pairs of variables from both domains were then tested by linear regression, yielding values between 0 (no correlation) and ±1 (perfect positive or negative correlation), along with a p-value, denoting the asymptotic significance of the regression model. These results can be interpreted as quantitative measure to which extent the musical interpretations of the singers are influenced by the acoustics of the room.

3 RESULTS

3.1 General trends

As a first step of analysis, 16 pairwise linear regressions were calculated for all room acoustic and musical descriptors and for *all* singers and musical pieces. Figure 1 shows all relations with a probability value (statistical significance) of $p < 0.2$, which were considered as serious trends. They show significant correlations between the spectral centroid, corresponding to the brightness of the singing voice, and the early decay time (EDT). The singers obviously tend to produce a brighter timbre of their voice in rooms with longer reverberation. At the same time, the spectral centroid significantly decreases with increasing bass ratio, i.e. the singers tend to follow the tonal color of the room response instead of compensating for it. The other timbre descriptor, namely the spectral flux, measuring the temporal variation of the power spectrum of the sound, is significantly decreasing with increasing EDT, suggesting that the singers lower the timbral variation of their performance as successive notes tend to overlap due to longer reverberation. This timbre descriptor also tends to decrease as G_{late} increases, which can be similarly interpreted as a reduced tendency to modulate the timbre of the sound in rooms with high late support. Both the loudness and the tempo of the singers tend to increase with the values of the early interaural cross correlation ($IACC_{early}$), considered as an inverse measure of the apparent width of the sound source. Hence, the singers tend to sing louder and faster as they perceive their own voice as less spacious. A reduction of the tempo with increasing reverberation time, as reported in earlier studies[6], has been observed in the present study only as a weak trend (p = 0.29).

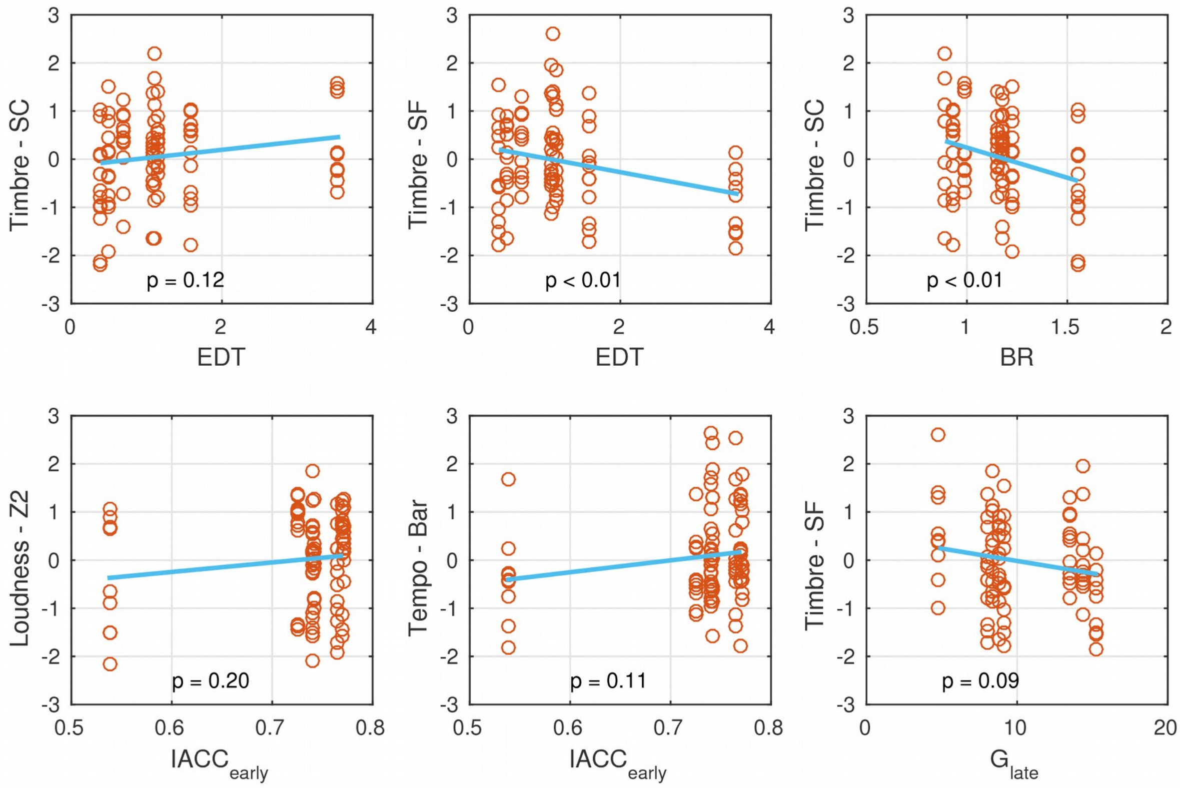

Figure 1 – Musical descriptors against room acoustical parameters, all in normalized units, for all singers and all pieces. The statistical significance of each linear regression is indicated as the probability of the null hypothesis, i.e. the *p*-value (p).

3.2 Individual strategies

The fact that relatively weak correlations between room acoustical parameters and performance features have been observed for the complete sample of singers and musical pieces can be the result of two different causes: Either there is no strong correlation between room acoustics and the way of singing, or these correlations are very individual, both for the personality of the musician and for the character of the musical piece, so that the dependencies can partly compensate each other. We have thus put a focus on interrelations which are obviously different for particular singers and particular musical pieces. Some of these individual patterns of reaction can be found for the loudness descriptor used. Considering the relation between loudness and reverberation time (EDT) for the three musical pieces and three different singers (Fig. 2A), it can be seen that singer 3 increased his loudness with increasing EDT, while singers 1 and 4 reduced their loudness, with singer 1 additionally adapting the extent of this reduction to the character of the musical piece. Similarly individual patterns can be observed for the interrelation between loudness and bass ratio (BR). While singer 3 reduces his loudness with an increasingly dark timbre of the room, singer 4 behaves exactly the other way around, and the reaction of singer 2 seems to depend on the musical piece he sings. It should be noted that most of the linear regressions in Fig. 2A and B do not reach statistical significance due to the small sample of singers, rooms, and musical pieces. They nevertheless demonstrate how individual the strategies of different singers can be, also confirming the results of earlier studies with instrumentalists[10].

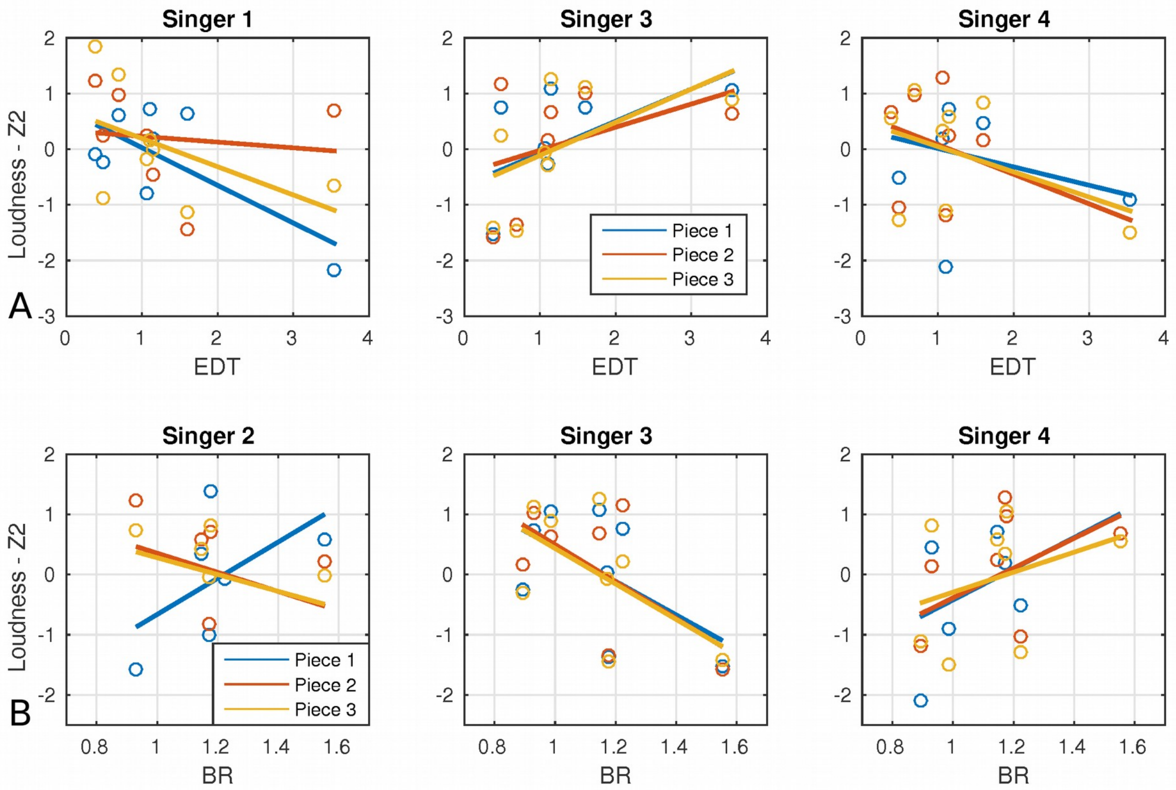

Figure 2 – Loudness of 3 different singers against early decay time (EDT, row A) and bass ratio (BR, row B).

4 CONCLUSION

This study presents the recordings of four singers who each performed three musical excerpts *a capella* in eight different room acoustical environments. From a comprehensive analysis of room acoustical parameters and musical performance descriptors extracted from the musical recordings, four parameters from each group were selected, which were shown to be musically and acoustically relevant by earlier studies. The statistical analysis of global interrelations, which are valid for all singers and all musical pieces, show significant correlations for the spectral centroid, which increases with increasing early decay time (EDT) and decreases with increasing bass ratio (BR), and for the spectral flux, which decreases with increasing EDT. The timbral setting of the voice thus seems to be the primary form of adaption to the room acoustical conditions, while the variations in tempo and loudness are either quite weak (Fig. 1), or they are individual for specific singers or specific pieces of music (Fig. 2), and cannot be generalized. This is in line with the analysis made for an instrumental musician in earlier work[8]. The duration (EDT) and the tone color (BR) of the reverberation tail have been identified as significant factors triggering performative adjustments, while $IACC_{early}$ and G_{late} seemed to be of minor relevance.

Beyond these general tendencies, several adaptation strategies were shown to be quite individual, both for the specific singer and for the specific piece of music. This was particularly noticeable for the individual adjustment of the sound level of the voice, both to the duration and the timbre of the room response. As shown for instrumental musicians[10], also singers seem to have their own strategies to adapt, consciously or not, to a variety of room acoustical conditions. In future work, these dependencies will be considered both through a larger sample of singers, rooms, and musical pieces, and through advanced statistical analysis, using for instance hierarchical or mixed linear models to account for the complexity of the problem.

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