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Singing in different performance spaces: The effect of room acoustics on singers' perception

Yvonne Gonzales Redman,[1] Joshua D. Glasner,[2] Dario D'Orazio,[3] and Pasquale Bottalico[4,a)]
[1]School of Music, University of Illinois Urbana Champaign, Champaign, Illinois 61820, USA
[2]School of Graduate and Professional Studies, Delaware Valley University, Doylestown, Pennsylvania 18901, USA
[3]Department of Industrial Engineering, University of Bologna, Bologna 40136, Italy
[4]Department of Speech and Hearing Science, University of Illinois Urbana Champaign, Champaign, Illinois 61820, USA

ABSTRACT:
Classical singers' performances vary across different acoustic environments. The changes in the delivery are influenced by the singer's perception of the venue's acoustics. This study investigated these relationships using nine professional or semi-professional classical singers. Participants performed Giordani's "Caro mio ben" aria in five venues, and the acoustic parameters reverberance (T30 and EDT), clarity (C80), early vocal support (STv), and tonal color (EDTf) were measured. From a factor analysis of the subjective analysis three major factors emerged that, we propose, would represent three generalized percepts of Room Supportiveness, Room Noiselessness, and Room Timbre. These percepts correlated significantly with objective acoustic parameters traditionally linked to vocal support, reverberation, and timbre. Room Supportiveness and Room Noiselessness significantly contributed to the singers' likability of the acoustic environment, while Room Timbre did not. This indicates that singers' perceptual preference for a performance space may be influenced by factors affecting both auditory feedback and vocal function. These findings underscore the need for performing space designers to consider the unique needs of all stakeholders, including listeners and performers. The study contributes to the bridging of the gap between subjective perceptions and objective measurements, providing valuable insights for acoustic design considerations.
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I. INTRODUCTION

While the acoustic design of concert halls and other performance venues has evolved over time, the fact remains that the acoustic environments are generally designed for the benefit of the listening audiences rather than that of the performers.[1,2] Since the 17th century, professional instrumentalists and singers have noted that an acoustic environment influences their perception of a performing space.[3] These subconscious or conscious observations may result in adjustments to their musical performance.[4,5] In two recent papers, Luizard *et al*. study the changes in singers' voice production across concert halls. It was confirmed that singers use individual adaptation patterns through several adaptation strategies. In the first one Bass Ratio and STearly were found as predominant monaural room criteria.[6] In the second one, Voice Intensity and IACClate were the most used voice and spatial parameters, respectively.[7] Furthermore, a recent investigation suggests that there is objective evidence of this phenomenon.[8] Therefore, it seems reasonable to conclude that the acoustic environment of a space is an important factor for the performing artist to consider when preparing a performance. Musical perception and subsequent conscious or subconscious responses by the performer represent critical considerations, because, "the singer, when he is performing, cannot know what he sounds like to the people who are listening."[9] This response is due, in part, to the natural masking that occurs in the human auditory system as the sound produced by the human voice is filtered or otherwise altered by bone conduction, tissue dampening, and an individual's head-related transfer function (HRTF).[9,10] Therefore, acoustic responses from a space may support or hinder a singer's self-perception and delivery.

A previous paper by the current authors explored quantitative changes to a singer's vibrato characteristics and pitch inaccuracy compared to objective acoustic parameters in five performance spaces. It appeared that singers may adjust their vocal production in different environments.[8] This present work is the second phase of the aforementioned study. It contextualizes the prior objective analysis by exploring the subjective perceptions of the singers and by comparing their descriptions and preferences with the acoustic parameters in each of the five spaces. As such, this paper expands upon our current understanding of how a room's acoustic environment influences a singer's performance from the perceptions, observations, and lived experiences of singing performers.

A. Acoustic measurements and preferences

Early literature related to ensemble musicians' preference of acoustic environment has focused primarily on

[a)]Email: pb81@illinois.edu

changes to reverberation and early reflection time. Marshall reported that instrumental soloists tend to prefer reverberation more than ensembles; noting that musicians seem to prefer early reflections between 17 and 35 ms.[11] Ternström observed performance-related changes as a function of reverberation time and other characteristics pertaining to a room's acoustic environment.[12] It was reported that a professional choir produces increased sound power in the long-term average spectra (LTAS) in more absorbent rooms and, conversely, increased formant peak frequency levels in rooms characterized by both short reverberation time and increased spectral energy in the low-frequency range.[11,12] Later studies explored additional room acoustical parameters such as early support and the possible influence on musical performance. Overall, these studies reported that dynamic level increased in rooms with short reverberation time and/or high support, but that the adjustment strategy is highly individualized.[5,13,14] Fry suggested that singers are unique in the sense that they need an acoustic balance between two distinct factors. Fry described the "time smear" from a sound's reverberation which provides singers the opportunity to hear and shape their musical phrasing in addition to the clarity necessary to "get the words across." The author suggested that an acoustic space with early high-frequency reflections would be optimal and named London's Wigmore Hall as such an example.[9]

Marshall and Meyer investigated the auditory impressions of both ensemble singers and soloists in a semi-anechoic laboratory with synthetic sound fields. They found that early reflections and reverberation contribute positively to ease of singing. More specifically, they reported that early reflections contribute positively to ease of singing if the value was measured as less than 40 ms. This observation is in direct contrast to the preferences of instrumental ensembles.[15] Later, Meyer clarified that vocal ensembles prefer the early decay time (*EDT*) of the stage environment to be no shorter than the reverberation time of the hall. Soloists, in contrast, have been found to prefer later reflections measuring approximately 60–120 ms, because of the post-masking effect caused by their own voice.[10] Meyer also noted that early reflections measuring approximately 25 ms (i.e., the direct sound field) positively contribute to a singer's sense of comfort while singing. Some researchers have suggested training somatosensory and kinesthetic awareness so as to mitigate the effects of different acoustic environments on a singer's performance.[9]

A more recent study seems to support and further clarify the subjective preferences of soloists. Gade summarized the most important characteristics that correspond with the subjective sense of acoustic environment. Specifically, soloists seem to prefer "modest reverberance" and "high clarity." The author suggested that an imbalance between these two acoustic characteristics can affect note clarity and intonation. In addition, room support was found to reduce the impression of effort and to allow for more dynamic contrast provided by low background noise. Without modest reverberance, high clarity, and adequate support, musicians tended to have a sense of "forced" playing which resulted in fatigue. Last, the preferred timbre or tonal color of a room was found to possess a balance between "warmth," "body," and "brilliance."[16]

B. Questionnaires and vocabulary

Past investigations have used interviews and questionnaires to ascertain the acoustical preferences of musical performers and conductors. Gade explored establishing a common language between descriptive perceptions of musicians and objective acoustic measurements to guide architects of concert halls. Overall, the study found that musicians tended to judge the acoustic environment of a hall along two dimensions: an overall quality judgment labeled "overall acoustic impression," and a second which included only "timbre."[17]

Influenced by the work of Gade and others, Dammerud provided questionnaires to orchestral musicians. These questionnaires contained open-ended questions and a five-point Likert scale for elements including physical comfort, ensemble elements of balance, dynamic ease, timbre, reflections, and overall impressions. The study concluded that players seem able to discern different acoustic conditions, but that they struggle to define the cause(s) of the differences they perceive.[18]

Similarly, Silingardi *et al.* compared survey questions with acoustic parameters; finding that high values of clarity (C80) and reverberation (T30) aligned with the preferred theatre of orchestral musicians among three historic Italian theatres.[19] Farina developed a questionnaire and distributed it to "highly qualified" music listeners regarding their perceptions of eight Italian theatres and halls,[20] influenced by a survey from Wilkens.[21] After finding linear correlations between subjective and physical evaluations, the questionnaire was reduced to nine subjective preferences in a five-point range and recommended nine objective parameters to guide future researchers.[20,21] The current study follows the previously outlined method. In so doing, it aims to determine the perceptions and acoustic preferences of professional singers.

II. EXPERIMENTAL METHOD

A. Participants

Six female and three male singers (average age 25.2 years) volunteered to take part in the experiment. The age, gender, and voice type of the nine participants are reported in Table I. The singers were predominantly graduate students in Western classical singing, with an average number of consistent classical singing lessons equal to 9.2 years.

B. Room descriptions

Participants were asked to sing in five unoccupied performing venues on the University of Illinois at Urbana–Champaign campus regularly used for musical

TABLE I. Characteristics of the sample, with age, gender, voice type, and number of years of experience.

ID	Age	Gender	Voice type	Years of experience
1	26	Female	Mezzosoprano	11
2	21	Female	Soprano	5
3	24	Male	Tenor	18
4	26	Female	Soprano	12
5	30	Female	Soprano	16
6	24	Female	Soprano	8
7	24	Male	Baritone	10
8	29	Male	Bass	10
9	23	Female	Mezzosoprano	7

performances. These include Smith Memorial Room, Smith Recital Hall, Krannert Center's Colwell Playhouse, Krannert Foellinger Great Hall, and Krannert Amphitheater. Please refer to Bottalico *et al.*[8] for a detailed description of measurement methods and room acoustic characteristics.

The Smith Memorial Room, a chamber music hall, boasts a "dry" acoustic characteristic, meaning its reverberation time is relatively low. Nevertheless, the balance between early and late reverberations (C80 = 2dB) is commendable, thanks to the effective sound reflections from the room's side and ceiling. A large rug mitigates reflections from the floor, thus preventing tonal unbalance from comb-filtering effects. This combination of acoustic properties makes the room well-suited for recordings.

Smith Recital Hall features a classic shoe-box style design, resulting in abundant side reflections. Like most shoe-box halls, its *EDT* is slightly shorter than its late reverberation, which envelops both the performers and the audience with a full, robust sound.

The Krannert Center's Colwell Playhouse is an ideal venue for dance performances, intimate musicals, and spoken word presentations. Despite its large size, the room is relatively dry acoustically. The wide range of C80 values confirms this dryness.

The Krannert Foellinger Great Hall is an impressive performance space, masterfully crafted by Cyril Harris, one of the 20th century's most influential acousticians. After experiencing the unsuccessful innovations of Beranek's hall at Lincoln Center, Harris adopted a more conventional approach while strategically selecting materials and shapes that enhance sound diffusion. The room's acoustic values are nearly ideal for symphonic music, with the slope of early decay slightly surpassing late reverberation, augmenting the impact of orchestral attacks and improving vocal intelligibility.

Finally, the Krannert Amphitheater is an open-air performance venue, designed in the style of ancient Greek and Latin amphitheaters. Although it's an open environment, there is mild reverberation caused by side reflections and the scattering effects from the risers. The former contributes to early reflection, while the latter creates delayed reflections. However, due to the absence of a ceiling and enclosed space, a late sound field does not form.

C. Protocol

Over a period of three hours, singers performed in each of the five unoccupied halls listed. The order of the halls was the same for all the participants due to limited availability of the spaces. Singers were directed to stand on a marked place on each stage and perform the same Italian art song ("Caro mio ben" by G. Giordani) a cappella. Following the performance, singers were led to a quiet space to fill out a questionnaire about their perceptions of performing in that space. They were then guided to the next hall and repeated the protocol. Preparation of the questionnaire used descriptive words following previous studies,[17,20] but items were rephrased into terms more familiar to American singers. There were 23 contrasting characteristics on analog scales (10 cm) and participants marked their subjective evaluation of each characteristic on each scale (see Table II). Two items were not filled out by all participants and were omitted, resulting in 21 total pairs.

D. Data processing

Data were processed statistically using R software following the scheme shown in Table III. The analysis was divided into two phases. In the first phase, the objective was to identify the set of significant affective impressions in the overall evaluation of the halls. A factor analysis (FA) was

TABLE II. Questions presented to the singers about their perceptions of performing in a space with the attributes presented at the two extremes of the visual analog scale.

Please select your overall impressions of singing in this space:	Difficult	Easy
	Unpleasant	Pleasant
	Dry	Reverberant
When not singing how do you perceive the overall sound level in this space?	Quiet	Noisy
	Disruptive	Peaceful
	Dull	Live
What was your impression of how your voice felt singing in this space?	Unsupported	Supported
	Dull	Brilliant
	Thin	Full
	Diffused	Concentrated
	Light	Heavy
	Weak	Powerful
	Muted	Amplified
What was your impression of how you heard yourself overall?	Difficult	Easy
	Weak	Strong
	Flat	Sharp
	Dark	Bright
	Muddy	Clear
How much do you like your sound in this space?	Not at all	Very much
How did you find the volume of this space for your voice?	Very small	Very large
Would you like to perform a non-amplified full vocal recital in this space?	Not at all	Very much

TABLE III. Data processing stages, techniques, and expected results.

Stage	Objective	Technique	Expected result
Phase I: Identification of significant subjective impressions in the assessment of the acoustics of the stage for singers.	Obtaining subjective impressions or semantic axes.	Factor analysis Cronbach's alpha.	Obtaining subjective impressions representative of the concepts singers use to describe the acoustics of the space.
	Analysis of the relation between subjective impressions and singing likability of the space	Mixed-effect linear regression.	Ordering subjective impressions or factors in relation to their significance in the singing likability of the space.
Phase II: Identification of the acoustical parameters on the stage calculated from the oral-binaural impulse responses that influence subjective impressions.	Calculating acoustical parameters from oral-binaural impulse response.	Procedures suggested by the ISO 3382-1 (Ref. 24)	Obtaining groups of acoustical parameters statistically independent that can be used as predictors in models.
	Analysis of the relationship between acoustical parameters and subjective impressions.	Mixed-effect linear regression.	Obtaining the impact of each independent acoustical parameters on singers' subjective impressions.

performed on the questionnaire. In this analysis, factors are represented as linear combinations of the original variables without inherent meanings. FA uncovers latent factors that explain observed correlations or covariances between variables. Assigning names to factors is a context-dependent, subjective process based on the examination of factor loadings.[22]

The second phase focused on obtaining the relationship between the hall's acoustics and subjective impressions. Mixed-effect linear regression is a statistical method used in various fields to analyze data with hierarchical structures. It considers both fixed effects (population-level relationships) and random effects (individual variations within groups).[23]

III. RESULTS

A. Phase I: Identification of significant subjective impressions in the assessment of the acoustics of the stage

1. Obtaining subjective impressions (semantic axes)

A factor analysis was performed using Ordinary Least Squares (OLS) to find the minimum residual (minres) solution. This analysis suggested grouping the 21 items in the questionnaire into three axes with a mean complexity of 1.4.

The cumulative variance explained by the first three axes is 100% (Table IV). The contribution of the original items to the axes was analyzed to determine the concept associated with each of them, thereby obtaining the following three factors or dimensions:

- *Factor 1*—The items that contribute most to this factor are Voice support (Unsupported-Supported), Voice fullness (Thin-Full), Pleasantness of singing (Unpleasant-Pleasant), Ease of singing (Difficult-Easy), Loudness of own voice (Weak-Strong), Voice brilliance (Dull-Brilliant), Voice gain (Muted-Amplified), Reverberance while singing (Dry-Reverberant), Voice power (Weak-Powerful), Pleasantness of room feedback while singing (Not At All-Very Much), Voice self-perception (Difficult-Easy), and Pleasantness of non-amplified singing (Not At All-Very Much), and Liveliness in the space when not singing (Dull-Live). This factor explains 56% of the variance in the original variables. Considering that this factor represents the assessment of the voice support provided by the room combined with the overall assessment from the singers' perspective, it was named **Room Supportiveness**.
- *Factor 2* includes the perception of **Room Noiselessness**. It is the assessment of room quietness and how this can affect voice clarity. It also includes the concepts of reverberance and room size. The items that contribute most to this factor are Peacefulness in the space when not singing (Disruptive-Peaceful), Voice clarity (Muddy-Clear), Room size for singing (Very Small-Very Large), and Pleasantness of room feedback while singing (Not At All-Very Much). The only opposite of this factor, with negative correlations, is the Reverberance while singing (Dry-Reverberant), and Noise perception in the space when not singing (Quiet-Noisy). This factor explains 28% of the variance in the original variables.
- *Factor 3* includes the perception of **Room Timbre**. It is the assessment of how the room affects spectral components. The items that contribute most to this factor are Voice timbre (Dark-Bright), Voice intonation (Flat-Sharp), and Liveliness in the space when not singing (Dull-Live). The only opposite of this factor, with negative correlations, is the Voice weight (Light-Heavy). This factor explains 16% of the variance in the original variables.

Consistency of perceptual space was verified with Cronbach's Alpha. The values for this reliability coefficient for the three dimensions ranged from 0.68 to 0.92 (Table IV), showing that these scales have considerable reliability.[24,25]

2. Analysis of the relation between subjective factors and singing likability of the room

A Linear Mixed Effects (LME) model was run with the response variable singing likability of the room rated between "Not at all" and "Very much." This question is bolded in Table IV. The fixed factors considered in the model were: Factor 1 (Room Supportiveness), Factor 2 (Room Noiselessness), and Factor 3 (Room Timbre), while

TABLE IV. Factor analysis of the items.

Items (extremes)	MR1	MR2	MR3
Ease of singing (Difficult-Easy)	0.77		
Pleasantness of singing (Unpleasant-Pleasant)	0.77		
Reverberance while singing (Dry-Reverberant)	0.66	−0.44	
Noise perception in the space when not singing (Quiet-Noisy)		−0.74	
Peacefulness in the space when not singing (Disruptive-Peaceful)		0.88	
Liveliness in the space when not singing (Dull-Live)	0.58		0.40
Voice support (Unsupported-Supported)	0.87		
Voice brilliance (Dull-Brilliant)	0.72		
Voice fullness (Thin-Full)	0.80		
Voice focus (Diffused-Concentrated)			
Voice weight (Light-Heavy)			−0.67
Voice power (Weak-Powerful)	0.63		
Voice gain (Muted-Amplified)	0.68		
Voice self-perception (Difficult-Easy)	0.56		
Loudness of own voice (Weak-Strong)	0.74		
Voice intonation (Flat-Sharp)			0.41
Voice timbre (Dark-Bright)			0.72
Voice clarity (Muddy-Clear)		0.80	
Pleasantness of room feedback while singing (Not At All-Very Much)	0.56	0.41	
Room size for singing (Very Small-Very Large)		0.48	
Pleasantness of non-amplified singing (Not At All-Very Much)	0.50		
% Variance explained	56	28	16
Cronbach's Alpha	0.92	0.77	0.68

subject id was considered as a random factor (see Table V). The estimate of standard deviation for subject id as a random effect was 0.02, whereas the residual standard deviation was 0.10. The singing likability of the room increased with a rate of 0.12 when the Voice Support factor increased, and with a rate of 0.07 when the Room Noiselessness factor increased. The factor Room Timbre was not a significant contributor to the singing likability of the room.

B. Phase II: Identification of the acoustical parameters on the stage calculated from the oral-binaural impulse response that influence subjective impressions

1. Calculating acoustical parameters from oral-binaural impulse response

The room acoustic parameters, calculated from oral-binaural impulse responses by DIRAC v6 and custom MATLAB codes, are shown in Table VI. They represent independent perceptual dimensions, namely, reverberance (*EDT*), definition (sound clarity; *C80*), loudness and self-hearing (early vocal support; *ST_v*), and low-frequency energy (*LFE*) or tonal color (*EDT_f*). *T30* values refer to the objective measurements of reverberation and were taken from measurements completed in the audience.

TABLE V. LME models fit by REML for the response variable singing likability of the room and the fixed factors Factor 1 (Room Supportiveness), Factor 2 (Room noiselessness), and Factor 3 (Room Timbre).

	Estimate	Std. Error	df	t value	p-value
(Intercept)	−0.11	0.08	40	−1.32	0.193
Factor 1	0.12	0.02	39	7.96	<0.001
Factor 2	0.07	0.02	41	3.41	0.002
Factor 3	−0.04	0.05	41	−0.87	0.391

TABLE VI. Room acoustic parameters, calculated from oral-binaural impulse responses by DIRAC v6 and custom MATLAB codes.

	ST_v (dB)	C80 (dB)	EDT (s)	EDT_f	T30 (s)
Smith Memorial Room	−10.5	16.2	0.40	0.77	1.04
Krannert Great Hall	−13.0	26.8	0.35	0.66	2.47
Krannert Colwell Playhouse	−4.90	25.8	0.34	0.77	1.42
Krannert Amphitheater	−11.4	22.8	0.38	0.52	0.68
Smith Recital Hall	−13.3	23.5	0.35	0.50	1.75

All parameters were averaged over the 500 Hz and the 1 kHz octave bands, except *ST_v*, which was averaged over the 125 Hz to 2 kHz octave bands, following Pelegrín-Garcia.[26] Two further criteria were calculated, even if they are not included in ISO standard.[24] First, such as criterion of *LFE*, *EDT_f* is used,[17] which is expressed as in Eq. (1),

$$EDT_f = \frac{EDT_{125\,\mathrm{Hz}} + EDT_{250\,\mathrm{Hz}}}{EDT_{500\,\mathrm{Hz}} + EDT_{1000\,\mathrm{Hz}}}. \qquad (1)$$

Second, *ST_v* is defined as in Eq. (2),

$$ST_v = L_r - L_d, \qquad (2)$$

where L_d is the direct field's energy, and L_r is the energy of the reflected field, both extracted from Oral-Binaural IRs measured using a Head and Torso Simulator (HATS, GRAS 45BB KEMAR, Holte, Denmark). The first term of the latter equation is integrated over a temporal window from 0 to 5 ms of the oral-binaural impulse response, whereas the reflect is integrated from 5 to 100 ms of the impulse response. This latter domain corresponds to the rest of IR because the significant reflections' energy is concentrated within the first 100 ms. Values of *ST_v* measured, respectively, at the left and right ear, are averaged.

In addition, the full-band version of the room parameters was tested in the statistical analysis, and the results showed a slightly larger proportion of variance explained by room acoustics, while the number of significant relationships between individual voice and room parameters was much reduced.

2. Analysis of the relationship between groups of design elements and affective impressions

Three Linear Mixed Effects (LME) models were run with the response variables Factor 1 (Room Supportiveness), Factor 2 (Room Noiselessness), and Factor 3 (Room Timbre). The fixed factors considered in the model were the objective acoustical parameters. Models were

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selected based on the Akaike information criterion.[27] The models were built using the R packages lme4 and lmerTest.

Regarding Factor 1 (Room Supportiveness), the best model included the *ST_v* as a fixed factor and subject id as a random factor. The estimate of standard deviation for subject id as a random effect was <0.01, whereas the residual standard deviation was 0.99. Factor 1 decreased with a rate of 0.28 when the *ST_v* increased. This finding suggested a more positive perception of the space in which the singer was singing when the level of the direct sound was higher compared to the reflected sound field.

Regarding Factor 2 (Room Noiselessness), the best model included the *EDT* as a fixed factor and subject id as a random factor. The estimate of standard deviation for subject id as a random effect was 0.24, whereas the residual standard deviation was 0.65. Factor 2 decreased with a rate of 16.40 when the *EDT* increased. This finding suggested that the room was perceived less silent/quiet when EDT values increased. It is important to note that Factor 2 considered the perception of the room noise profile both when the singer was singing and when they were not singing.

Regarding Factor 3 (Room Timbre), the best model included the *EDT_f* as a fixed factor and subject id as a random factor. The estimate of standard deviation for subject id as a random effect was smaller than 0.01, whereas the residual standard deviation was 0.35. Factor 3 decreased with a rate of 1.95 when the *EDT_f* increased. This finding suggested an increase in the "lighter/brighter/sharper" perception of their own voice in the room when the *EDT_f* values decreased. The output of the three models including Estimates, Standard Error, degree of Freedom, t-values, and p-values, are reported in Table VII.

TABLE VII. LME models fit by REML for the response variables Factor 1, Factor 2, and Factor 3 the objective acoustical parameters.

	Estimate	Std. Error	df	t value	p-value
Factor 1 (Room Supportiveness)					
(Intercept)	3.74	0.54	43.0	6.87	<0.001
ST_v	−0.28	0.05	43.0	−5.78	<0.001
Factor 2 (Room Noiselessness)					
(Intercept)	7.02	1.58	35.4	4.44	<0.001
EDT	−16.40	4.33	35.0	−3.79	<0.001
Factor 3 (Room Timbre)					
(Intercept)	2.35	0.32	43.0	7.29	<0.001
EDT_f	−1.95	0.50	43.0	−3.92	<0.001

IV. DISCUSSION

The aim of the current study was to investigate the relationship between the singer-reported likability of a performing space and the acoustic environment of that space. It analyzed the subjective evaluations made by nine singers of twenty-one perceptual characteristics of five different performing spaces. To do so, it used a factor analysis of those subjective evaluations to describe three overarching percepts for singers related to the acoustic environment: Room Supportiveness, Room Noiselessness, and Room Timbre. This study also analyzed the association between each of the aforementioned singer percepts and both singer-reported likability and objective acoustic parameters.

Overall, both Room Supportiveness and Room Noiselessness significantly contributed to singer-reported likability of a performing space. Additionally, *ST_v* was found to be significantly negatively associated with Room Supportiveness, *EDT* was found to be significantly negatively associated with Room Noiselessness, and *EDT_f* was found to be significantly negatively associated with Room Timbre. That is to say, a room's acoustic environment does seem to contribute to how much a singer enjoys singing in a performing space. Moreover, factors that contribute to how well a singer is able to monitor feedback seem to influence their perceptual evaluations more than a room's timbral characteristics.

A. Subjective acoustic impressions and likability

Past literature has reported that musicians are capable of discerning differences in the overall acoustic environment of a performing space, but that their awareness of individual acoustic characteristics is not as pronounced.[18] Similarly, Gade[17] suggested a two-category paradigm to explain musician preference: Overall Acoustic Impression and Timbre. Expanding upon these two investigations, the present inquiry found that three semantic factors—or singer percepts—accounted for 100% of the variance for singer-reported subjective characterizations of a room's acoustic environment. These factors were termed Room Supportiveness, Room Noiselessness, and Room Timbre.

1. Room supportiveness

Room Supportiveness explained the majority of the variance in the original variables (56%). This semantic factor seems to refer to perceptual characteristics which may influence a singer's sense of vocal effort given a particular vocal demand.[28] It was found to positively contribute to how much a singer liked performing in a space. Past study has suggested a relationship between room acoustics and vocal effort.[29–31] Furthermore, there is evidence that singers adjust their vocal performance when singing in different spaces—potentially non-volitionally.[6,8] As such, Room Supportiveness seems to account for a solo singer's experience as it influences their vocal function and performance.

2. Room noiselessness

Room Noiselessness was found to significantly explain 28% of the variance in the subjective characteristic variables. It is important to note that the variables Reverberance while singing and Noise perception in the space when not singing were negatively correlated with Room Noiselessness, whereas all others were positively correlated with this factor.

While both Room Supportiveness and Room Noiselessness contain subjective characteristics which are related to auditory-feedback, Room Noiselessness seems most related to two overall perceptual categories: a room's noise profile and its perceived reverberance. While there is evidence that musicians have a robust ability to process sound even in the presence of background noise,[32] the negative effects of room noise have been discussed extensively in the literature.[33,34] As such, the positive correlation between Room Noiselessness and singer-reported likability of a performing space seems quite evident; however, the inclusion of subjective characteristics related to perceived reverberance within this factor requires at least some consideration.

This study found that singers tended to rate the likability of a performing space as lower if the perceived reverberance while singing was high. At first, this observation might seem to contradict past literature which indicates that musicians prefer a reverberant space to a non-reverberant space.[10,16] In fact, the inclusion of perceived reverberance in both Room Supportiveness and Room Noiselessness factors suggests a nuanced interpretation of the work of Gade,[16] Fry,[9] and Meyer:[10] soloists and singers prefer rooms that are characterized by some reverberation, but not too much. In other words, this study confirms past literature that suggests that soloists prefer "modest reverberance,"[16] but it groups reverberation with both the way in which a room positively contributes to a singer's vocal function and the way in which a room may negatively mask a singer's resultant performance. Considered in amalgam, the subjective characteristics contained within the Room Noiselessness factor seem to contribute positively to singer-reported likability of a performing space. Solo singers prefer performing in spaces that have a low noise profile and modest amounts of reverberation.

3. Room timbre

While Room Timbre was not found to be a significant factor in relation to singer-reported likability of a performing space, it was included in all phases of this analysis due to its reported perceptual influence in past literature.[17,18] The factor accounted for 16% of the variance in the original variables.

The curious aspect of the results related to Room Timbre is that singers—and musicians in general—seem to report timbre as being an important subjective characteristic related to their preference of an acoustic environment.[4,17,18] Yet, these results suggest that singers are keen to perform in spaces which positively influence their performance and the ability of others to receive and enjoy their performance. In contrast, the timbre of a performing space does not seem to contribute significantly to singer-reported likability of that space as do supportiveness and noiselessness (i.e., function- and performance-related factors). While the inherent timbre of a space inevitably contributes to the way in which sounds are filtered, it is possible that singers use the term timbre as a "catch-all" when they truly intend to characterize the perceived reverberance, clarity, and envelopment of an acoustic environment.

B. Objective acoustical parameters

Past inquiry has investigated the objective relationships between measures of a room's acoustic environment and subjective perceptions of musicians; however, few studies have attempted to do this for singer-specific perceptions. Additionally, there were a few variables in the current study for which the direction of the relationship with a semantic factor required further explanation.

1. Vocal support

ST_v represents the difference between the level of energy in the reflected field and the level of energy in the direct field.[31] As such, it represents an environment in which a higher proportion of energy is in the direct sound field compared to the reflected sound when its calculated value is negative. This study found a significant negative relationship between *ST_v* as measured binaurally by a HATS device and described by Room Supportiveness. That is to say, as the energy in the reflected sound decreased compared to the energy in the direct sound field, the singer-reported likability of an acoustic environment increased. While speakers and singers have different acoustic needs and produce distinct dynamic ranges,[35] vocal support does seem to be represented within the semantic factor of Room Supportiveness. As such, it contributes to the degree to which a singer prefers a performance space.

2. Perceived reverberance

This study found that Room Noiselessness was significantly negatively correlated with *EDT*. While past studies have found that some perceived reverberance is preferred by soloists,[9,10] the findings from this study confirm that high *EDT* values may constitute "too much of a good thing." Or, as Marshall *et al*. suggested, "a temporal window exists outside of which reflections are judged adversely."[11] Additionally, while the findings from this study confirm the negative relationship between musician preference of an acoustic environment and *EDT* (i.e., soloists prefer "modest reverberance" per Gade[16]) it is possible that singers have different thresholds for perceived reverberance than musicians as a whole.

3. Frequency variation of perceived reverberance

While Room Timbre was not found to significantly contribute to singer-reported likability of an acoustic environment, it was found to be significantly negatively correlated with *EDT_f*. A foundational study related to this topic has shown that the frequency variation of perceived reverberance (*EDT_f*) is correlated with subjective evaluations of timbre.[17] The current study is in agreement with Gade's work given that both demonstrate a significant negative relationship between *EDT_f* and subjective evaluations of timbre. As such, it seems that the semantic factor Room Timbre accurately represents a singer's subjective evaluation of the timbre of an acoustic environment. Furthermore, this finding supports the inference that singers are more influenced by Room Supportiveness and Room Noiselessness than by Room Timbre.

C. Limitations

While a strength of this study is the use of multiple professional performance spaces, its method was limited by the lack of randomization on the order of those performance spaces. Instead, the order in which a singer performed in each successive venue was determined by the availability of the performance spaces. This lack of randomization could have introduced ordering effects of a sort, thereby influencing the relative likability and perception of the acoustic environments. Both of these possible effects could also be negatively influenced by increasing performer fatigue throughout the duration of the protocol. Future studies should consider and counteract the possibility of ordering effects by randomizing the order of the performance spaces.

D. Practical significance

One of the more interesting aspects of the binaural analysis of room acoustic parameters using a HATS device is that it approximates the aural experience of a singing performer. As such, it provides architectural acousticians and singing voice scientists with the ability to understand more fully how an acoustic environment impacts a singer's performance and their subjective perceptions of a space. This method allows researchers to address Beranek's observation that architectural acoustics frequently prioritizes the aural experience of the listener over that of the performer.[1] Given the increasing evidence that a room's acoustic environment influences both vocal function and a singer's sense of vocal effort,[6,8,29–31] it seems reasonable to conclude that the acoustic needs of singers (ensembles and soloists) should be considered as distinct from those of other musicians. Furthermore, voice training might begin to include improved strategies to maintain vocal performance despite inevitable changes in auditory feedback.

V. CONCLUSION

This paper reported the findings of a study that investigated the relationship between singer-reported subjective evaluations and objective acoustic parameters of performance spaces. It further classified twenty-one subjective evaluations using semantic factor analysis and described them using three singer percepts: Room Supportiveness, Room Noiselessness, and Room Timbre. Those three factors were found to significantly correlate with objective acoustic parameters that have been shown historically to be related to subjective perceptions of vocal support, reverberation, and timbre. Overall, Room Supportiveness and Room Noiselessness were found to significantly contribute to singer-reported likability of an acoustic environment; however—and in contrast to prior reports—Room Timbre was not found to significantly contribute to how much a singer liked performing in a space. It seems that singers may ascertain their perceptual preference of a performance space based on factors that may influence both their auditory feedback and their volitional or non-volitional vocal function and performance. As a result, it may be worthwhile for those who design performing spaces to consider the unique needs of all stakeholders including listeners, singers, instrumentalists, soloists, and ensemble performers.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Ethics Approval

The use of human subjects for this research was approved by the Office for the Protection of Research Subjects at the University of Illinois Urbana-Champaign (IRB #18179). Informed consent was obtained from all participants.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

[1]L. Beranek, *Concert Halls and Opera Houses: Music, Acoustics, and Architecture* (Springer-Verlag, New York, 2004), pp. 15–18.
[2]T. Lokki, J. Pätynen, A. Kuusinen, and S. Tervo, "Disentangling preference ratings of concert hall acoustics using subjective sensory profiles," J. Acoust. Soc. Am. **132**(5), 3148–3161 (2012).
[3]Z. Schärer Kalkandjiev and S. Weinzierl, "The influence of room acoustics on solo music performance: An experimental study," Psychomusicol.: Music Mind Brain **25**(3), 195–207 (2015).
[4]V. L. Jordan, *Acoustical Design of Concert Halls and Theatres: A Personal Account* (Applied Science, London, 1980), pp. 81–83.
[5]K. Ueno, K. Kato, and K. Kawai, "Effect of room acoustics on musicians' performance. Part I: Experimental investigation with a conceptual model," Acta Acust. Acust. **96**, 505–515 (2010).
[6]P. Luizard and N. H. Bernardoni, "Changes in the voice production of solo singers across concert halls," J. Acoust. Soc. Am. **148**(1), EL33–EL39 (2020).
[7]P. Luizard, J. Steffens, and S. Weinzierl, "Singing in different rooms: Common or individual adaptation patterns to the acoustic conditions?," J. Acoust. Soc. Am. **147**(2), EL132–EL137 (2020).
[8]P. Bottalico, N. Łastowiecka, J. D. Glasner, and Y. G. Redman, "Singing in different performance spaces: The effect of room acoustics on vibrato and pitch inaccuracy," J. Acoust. Soc. Am. **151**(6), 4131–4139 (2022).
[9]D. Fry, "The singer and the auditorium," J. Sound Vib. **69**(1), 139–142 (1980).
[10]J. Meyer, "Understanding the orchestral stage environment from the musician's, singer's, and conductor's point of view," in *Wallace Clement Sabine Centennial Symposium*, Cambridge, MA (1994), pp. 93–96.

https://doi.org/10.1121/10.0021331

[11]A. H. Marshall, D. Gottlob, and H. Alrutz, "Acoustical conditions preferred for ensemble," J. Acoust. Soc. Am. **64**, 1437–1450 (1978).
[12]S. Ternström, "Long-time average spectrum characteristics of different choirs in different rooms," Speech Transm. Lab. Quart. Prog. Status Rep. **30**(3), 15–31 (1993).
[13]S. Bolzinger, O. Warusfel, and E. Kahle, "A study of the influence of room acoustics on piano performance," J. Phys. IV. France **04**(C5), C5-617–C5-620 (1994).
[14]K. Kawai, K. Kato, K. Ueno, and T. Sakuma, "Experiment on adjustment of piano performance to room acoustics-analysis of performance coded into midi data," in *Proceedings of the ISRA*, Toronto, Canada (2013).
[15]A. Marshall and J. Meyer, "The directivity and auditory impressions of singers," Acustica **58**, 130–140 (1985).
[16]A. Gade, "Classical musicians' perception of room acoustic conditions," Psychomusicol.: Music Mind Brain **25**(3), 232–235 (2015).
[17]A. Gade, "Investigations of musicians' room acoustic conditions in concert halls. Pt. II: Field experiments and synthesis of results," Acustica **69**, 249–262 (1989).
[18]J. Dammerud, "Stage acoustics for symphony orchestras in concert halls," Ph.D. thesis, u557061, University of Bath, Bath, UK (2009).
[19]V. Silingardi, D. D'Orazio, S. De Cesaris, and M. Garai, "Musicians' subjective perception and objective acoustic descriptors in the stages," in *Proceedings of AIA-DAGA 2013 Conference*, DEGA (2013), Vol. 1, pp. 1–349.
[20]A. Farina, "Acoustic quality of theatres: Correlations between experimental measures and subjective evaluations," Appl. Acoust. **62**, 889–916 (2001).
[21]H. Wilkins, "Mehrdimensionale Beschreibung subjektiver Beurteilungen der Akustik von Konzertsälen" ("Multidimensional description of subjective assessments of the acoustics of concert halls"), Acustica **38**(10), 10–23 (1977).
[22]S. A. Mulaik, *Foundations of Factor Analysis* (CRC Press, Boca Raton, FL, 2009).
[23]V. A. Brown, "An introduction to linear mixed-effects modeling in R," Adv. Methods Pract. Psychol. Sci. **4**(1), 1–19 (2021).
[24]ISO3382-1:2009, "Acoustics—Measurement of Room Acoustic Parameters—Part 1: Performance Spaces" (International Organization for Standardization, Geneva, Switzerland, 2009).
[25]D. L. Streiner, "Starting at the beginning: An introduction to coefficient alpha and internal consistency," J. Pers. Assess. **80**(1), 99–103 (2003).
[26]D. Pelegrín-Garcia, "Comment on 'Increase in voice level and speaker comfort in lecture rooms,'" J. Acoust. Soc. Am. **129**(3), 1161–1164 (2011).
[27]H. Akaike, *Selected Papers of Hirotugu Akaike* (Springer, New York, 1998), pp. 199–213.
[28]E. J. Hunter, L. C. Cantor-Cutiva, E. van Leer, M. Van Mersbergen, C. D. Nanjundeswaran, P. Bottalico, M. J. Sandage, and S. Whitling, "Toward a consensus description of vocal effort, vocal load, vocal loading, and vocal fatigue," J. Speech. Lang. Hear. Res. **63**(2), 509–532 (2020).
[29]P. Bottalico, "Speech adjustments for room acoustics and their effects on vocal effort," J. Voice **31**(3), 392.e1–392.e12 (2017).
[30]P. Bottalico, S. Graetzer, and E. J. Hunter, "Effects of speech style, room acoustics, and vocal fatigue on vocal effort," J. Acoust. Soc. Am. **139**(5), 2870–2879 (2016).
[31]D. Pelegrín-Garcia and J. Brunskog, "Prediction of vocal effort and speakers' comfort in lecture rooms," in *Proceedings of Inter-Noise 2009*, Ottawa, Canada (2009).
[32]A. Parbery-Clark, E. Skoe, and N. Krause, "Musical experience limits the degradative effects of background noise on the neural processing of sound," J. Neurosci. **29**(45), 14100–14107 (2009).
[33]M. Don and J. Eggermont, "Analysis of click-evoked brainstem potentials in man using high-pass noise masking," J. Acoust. Soc. Am. **63**, 1084–1092 (1978).
[34]N. Russo, T. Nicol, G. Musaacchia, and N. Kraus, "Brainstem responses to speech syllables," Clinic. Neurophysiol. **115**, 2021–2030 (2004).
[35]D. D'Orazio, S. D. Cesaris, A. Tovo, L. Guerra, and M. Garai, "Objective musician's criteria in Italian historical theatres," in *Proceedings of the 22th International Congress on Sound and Vibration, ICSV22* (2015), Vol. 1, pp. 1–8.