AN INVESTIGATION INTO THE EFFECT OF ACOUSTICS ON VOCAL STRAIN OF OPERA SINGERS

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Objectives: This paper will report some of the final results of a doctoral study on the effect of acoustics on vocal strain of Opera singers. The research presents singers' objective voice dosimetry and subjective perception data together with the room acoustic parameters with the aim of establishing the preferred practice room conditions for Opera singers.

Methodology: For this purpose 117 Opera singers from the Royal Academy of Music participated in the research. The pilot stage of the research was undertaken at the acoustic laboratories of London South Bank University in order to validate the research methodology in controlled environment, and the field stage was undertaken at four practice rooms of Royal Academy of Music. Singers' subjective data was collected via questionnaires validated during the pilot stage, and singers' objective voice dosimetry data was collected via Ambulatory Phonation Monitor. Room acoustic measurements were undertaken separately for each practice room when the rooms were unoccupied. Statistical analysis were performed to establish the relationship between the room acoustics and the singers' data.

Results: The students' subjective response to the different acoustic conditions of the practice rooms showed significant change and very strong correlations were observed with the measured T30 room acoustic parameter at the 4kHz octave band and C80 parameter at 500Hz to 4kHz. Using this information and the practice room geometries, Opera singers' ideal practice room conditions were established.

Keywords: Ambulatory Phonation Monitor, practice room acoustics, opera singers, voice dosimetry, vocal loading

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1. Introduction

Professional classical singing requires dedication and a significant amount of practice in order to properly sing the challenging pieces. Classical singers not only practice to become an expert in their techniques but also must understand the context, emotions and delivery of each musical piece. Acoustics of practice rooms are crucial as the singers spend most of their learning process in these rooms. According to Lamberty [1] weekly use of practice rooms in music schools by music students can reach 40 hours, which proves the importance of these spaces.

Previous research on singers' voice focused on the voice and vocal health issues. This allowed improved treatments and techniques in the clinical practice for singers' vocal health. However, little research has been undertaken on how room acoustics affect the voice dosimetry and perception of classical singers. The aim of this research was to understand the changes in Opera singers' objective and subjective responses due to change in the acoustics of their practicing environment. This would allow the relationship between room parameters and the subject's parameters to be determined so that a preferable practicing environment for the Opera singers could be designed.

2. Methodology

The research has been undertaken in two stages: the pilot and the field stage. The research methodology including the questionnaire and the equipment to be used for the field stage were validated in the pilot stage which was undertaken with a total of 62 Opera singers using extreme environments; a reverberant, semi-reverberant and an anechoic chamber.

The field stage was undertaken with a total of 55 Opera singers. Four acoustically different practice rooms at the Royal Academy of Music which are mainly used by the Opera singers were chosen. The data were collected in three steps: singers' objective data collection, singers' subjective data collection, and room data collection.

2.1 Singers' Objective Data Collection

Vocal loading is known as the stress inflicted on the vocal folds during phonation.[2, p125] In order to track singers' vocal loading and collect voice dosimetry data, two equipment were used: an Ambulatory Phonation Monitor (APM) and a Class 1, Norsonic 140 sound level meter.

2.1.1 Objective Voice Dosimetry collection via Ambulatory Phonation Monitor (APM)

APM is a portable device composed of an accelerometer which is attached to singers' glottis. The accelerometer detects the vocal fold vibrations and provides voice dosimetry data including phonation time (P_t, sec), time-average sound pressure level (SPL, dB), frequency ($F0_{average}$ and $F0_{mode}$, Hz), cycle dose (D_c) and distance dose (D_d, meters). These voice dosimetry parameters are known as vocal loading parameters, and the device is used in order to track the changes in each of these parameters due to change in the acoustics of the practice rooms.

Prior to measurements, the device needs to be calibrated for each singer in order to introduce the full range of the singer to the device. After calibration process, in order to collect singers' voice dosimetry data, the singers were given two tasks: to sing "scales" and a "song" of their own choice for two minutes and to repeat the same tasks in each of the four practice rooms. As in their real practice environment, they were asked to sing the scales first as a warm-up and then the song. The total singing duration in each practice room were four minutes non-stop (two-minute scales, two-minute song) and the total voice dosimetry measurement duration was 16 minutes with each singer.

2.1.2 Objective Voice Dosimetry collection via Sound Level Meter

During pilot stage it is found out that APM only provides time-average unweighted sound pressure levels, in order to obtain frequency based data for a more detailed analysis, a Class 1 Nor140 sound level meter was fixed at 1.5 m away from the singers during monitoring. Sound power levels for each octave band were calculated from the measured sound pressure levels for each singer via Equation 1 [35] where L_{TOTAL} is the sum of direct and reverberant sound pressure levels, L_w is the sound power level, r is the distance of receiver from the source and R_c is the room constant.

$$L_{TOTAL} = Lw + 10\log\left(\left(\frac{Q}{4\pi r^2}\right) + \left(\frac{4}{Rc}\right)\right) \tag{1}$$

R_c for each room was calculated for each octave band frequency using Equation 2 [3] where S is the total area of room surfaces, α is the average sound absorption of those surfaces at each octave band.

$$Rc = \left(\frac{\mathbf{S\alpha}}{(\mathbf{1-S\alpha})}\right) \tag{2}$$

Sound absorption for each room at each octave band frequency was calculated via Sabine's formula presented in Equation 3 [4] using measured T30 values.

$$T30 = 0.161\left(\frac{V}{\Sigma Si\alpha i + 4mV}\right) \tag{3}$$

2.2 Singer's Subjective Data Collection

2.2.1 Room Questionnaire

In order to collect singers' subjective data regarding the rooms, a questionnaire was developed. The questionnaire was composed of nine questions of which the singers were asked to rate on a seven-point Likert-type scale. The first five questions were related to room acoustic parameters whereas the last four questions were about their perceived effort and overall impression of the rooms. The questions are presented below in Table 1[5]. The singers were asked to complete the questionnaire right after their voice dosimetry collection in each room.

Table 1: Room Questionnaire in order to collect singers' subjective data with preferred values

	Subjective Parameter	Preferred Rating
1	Loudness How do you perceive your sound level in this room?	4 (sufficient) 5 (loud)
2	Clarity How would you rate the degree to which notes are distinctly separated and clearly heard?	4 (clear)
3	Reverberance How would you rate the persistence of sound in this room?	4 (balanced) 5 (reverberant)
4	Background noise How would you rate the background noise levels in this room?	2 (very weak) 3 (weak)
5	Size of the room How would you rate the size of this room?	4(sufficient) 5 (large)
6	Pleasure of singing in this room How would you rate your pleasure of singing in this room?	5 (good) 5 (very good)
7	Voice feeling How would you rate your voice feeling in this room?	4 (as usual) 5 (strong)
8	Singing effort How would you rate your effort singing in this room?	4 (as usual)
9	Overall Impression How would you rate the acoustical quality of this room?	5 (good) 6 (very good)

2.2.2 Singers' preferred ratings

In addition, after completion of the room questionnaire, regardless of the rooms they have sung in, the singers were also asked about what rating they would ideally prefer on the 7-point Likert type scale for each subjective parameter in order to find out Opera singers' preferred ratings and their preferences were separately documented in an Excel sheet. In further analysis, these preferred ratings were targeted for each subjective parameter in order to find out ideal practice room conditions for the Opera singers.

2.3 Room Data Collection

Room acoustic measurements of each practice room were undertaken using the exponential swept sine (e-sweep) technique using the WINMLS software. A laptop connected to a Norsonic (Nor280) power amplifier linked to a Norsonic (Nor275) hemi-dodecahedron loudspeaker and an Earthworks M30BX class 1 microphone was used when the rooms were unoccupied at a minimum of six measurement positions. Parameters including Clarity Index (C80), Reverberation Time (T30), and Early Decay Time (EDT) were measured at each octave-band for each room. Results of measured reverberation times in each practice room is presented in Figure 1[5]. Due to small size of the rooms, Strength (G) parameter was calculated from the measured Reverberation Time using the following formula [6]:

$$G_{\text{exp}} = 10 \log_{10}\left(\frac{T}{V}\right) + 45\,\text{dB} \tag{4}$$

In addition, background noise measurements were undertaken using a NOR 140 sound level meter, again when the rooms were unoccupied. Here, the aim was to measure the background noise levels at the time when the singer's voice dosimetry measurements were collected, pragmatic two-minute representative background noise measurements were done immediately after the data collection of each subject when the room under measurement was unoccupied but adjacent practice rooms were in use. In order to find the representative noise levels during the time of singers' measurements, the two-minute background noise levels ($L_{Aeq,2min}$) collected after each singer (N=55) in each practice room were logarithmically averaged for each room.

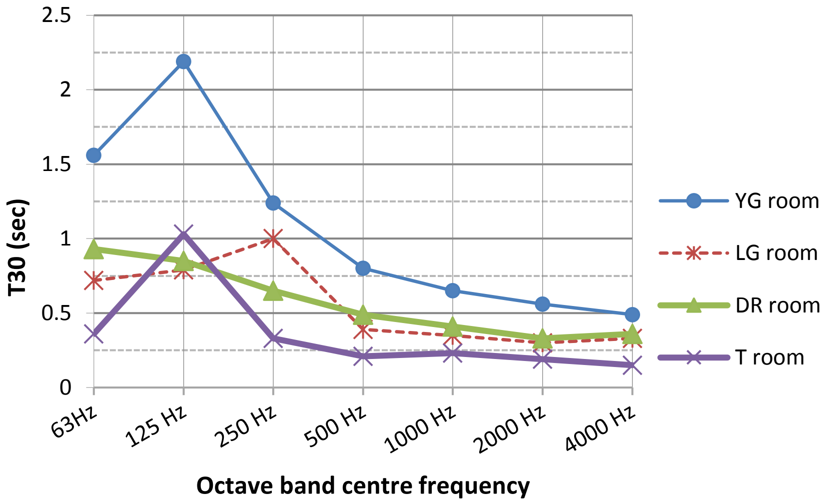

Figure 1: The measured reverberation times, T30 (s) in octave bands for each RAM practice room

2.4 Statistical Analysis

The measurement results were analysed using IBM SPSS Statistics 21. In order to find the difference of singer's data between the practice rooms a One-Way Repeated Measures ANOVA test was conducted. According to the results of one-way repeated measures ANOVA tests, the parameters that showed significant difference between RAM practice rooms further analysed together with Pearson Correlation Analysis in order to find the correlation between room data and the singers' data. The parameters which have shown significant correlation were further analysed using regression analysis to predict the target values of these parameters which correspond to singers' "preferred" ratings in practice rooms.

3. Results

According to the results of one-way repeated measures ANOVA tests conducted for singer's data, the voice dosimetry data collected via APM and SLM did not show any statistically significant change, but the singers' subjective data did show a significant change.

Parameters that showed significant difference between RAM practice rooms further analysed via Pearson Correlation Analysis. Therefore, singers' subjective data were analysed together with the room data in order to find the correlation between room parameters and the singers' subjective parameters.

An interesting result of the Pearson Correlation analysis was that C80 and T30 parameters were in consistent agreement with the following five subjective parameters at 4 kHz: Reverberance, Voice feeling, Singing Effort, Pleasure of Singing, and Overall Impression, as shown below in Table 2[5] and Table 3[5] respectively.

Table 2: Pearson Correlation Analysis Results for C80 room parameter

Subjective Parameter	Room Parameter	Pearson Correlation	P (Sig. 2-tailed)
Reverberance	$C80_{(500Hz)}$	-.986	0.014
	$C80_{(1kHz)}$	-.988	0.012
	$C80_{(2kHz)}$	-.957	0.043
	$C80_{(4kHz)}$	-.996	0.004
Pleasure of singing	$C80_{(500Hz)}$	-.977	0.023
	$C80_{(1kHz)}$	-.986	0.014
	$C80_{(2kHz)}$	-.999	0.001
	$C80_{(4kHz)}$	-.951	0.049
Voice feeling	$C80_{(500Hz)}$	-.980	0.02
	$C80_{(1kHz)}$	-.987	0.01
	$C80_{(2kHz)}$	-.958	0.04
	$C80_{(4kHz)}$	-.989	0.01
Singing Effort	$C80_{(500Hz)}$	.984	0.02
	$C80_{(1kHz)}$	.991	0.01
	$C80_{(2kHz)}$	.965	0.03
	$C80_{(4kHz)}$	.991	0.01
Overall Impression	$C80_{(500Hz)}$	-.978	0.02
	$C80_{(1kHz)}$	-.987	0.01
	$C80_{(2kHz)}$	-.999	0.001
	$C80_{(4kHz)}$	-.953	0.047

Table 3: Pearson Correlation Analysis Results for T30 room parameter

Subjective Parameter	Room Parameter	Pearson Correlation	P (Sig. 2-tailed)
Reverberance	$T30_{(4kHz)}$	.955	0.045
Pleasure of singing	$T30_{(4kHz)}$	.998	0.002
Voice feeling	$T30_{(4kHz)}$	.955	0.045
Singing Effort	$T30_{(4kHz)}$	-.963	0.037
Overall Impression	$T30_{(4kHz)}$	.998	0.002

As a second step, the parameters that showed correlation were further analyzed using regression analysis in order to find the minimum and maximum values of the room parameters that provide the target preferred ratings of the Opera singers. Regression analysis was conducted by considering the room parameters as independent variables (x-axis) as they are not dependent on the subjective parameters and by considering the subjective parameters as dependent variables (y-axis) as they depend on the room parameters. Examples of regression models obtained between the subjective parameter and the room parameter are presented between Reverberance subjective parameter and $C80_{(4kHz)}$ and $T30_{(4kHz)}$ room parameters in Figure 2[5] and Figure 3[5] respectively.

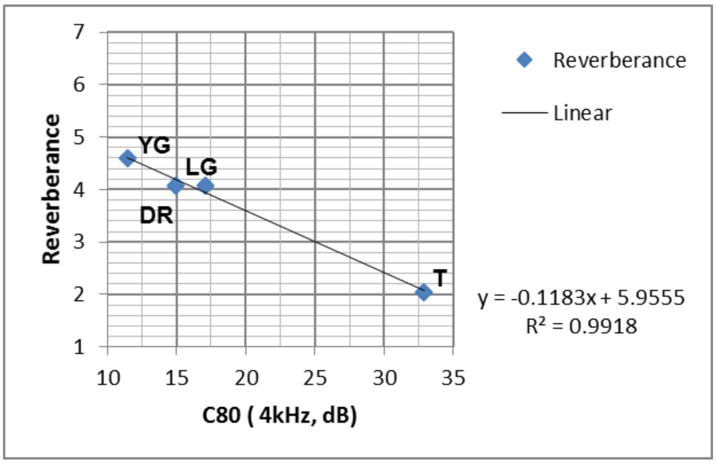

Figure 2: Regression model between subjective Reverberance parameter and $C80_{(4kHz)}$ room parameter. Points show mean values for Reverberance parameter answered via N=55 singers in each practice room.

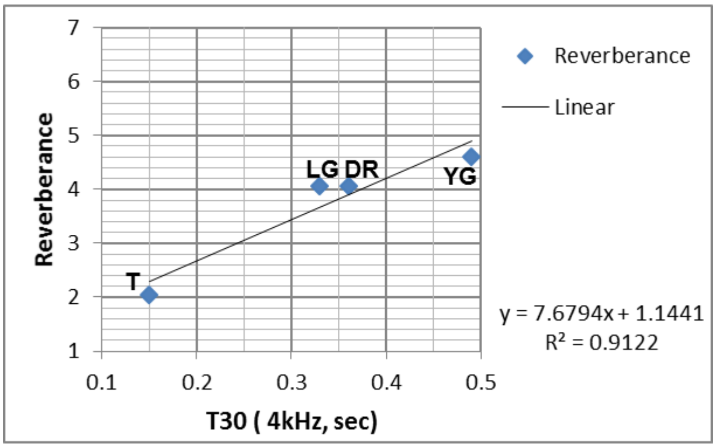

Figure 3: Regression model between subjective Reverberance parameter and $T30_{(4kHz)}$ room parameter. Points show mean values for Reverberance parameter answered via N=55 singers in each practice room.

The regression equations obtained via analysis were used in order to predict the room parameter values that correspond to singers' preferred ratings. Since the preferred ratings showed variation for each subjective parameter, a range was introduced as a target. The values corresponding to singers' preferred ratings according to the results of the regression analysis are presented below in Figure 3[5] and Figure 4[5] for C80 and T30 room parameters at the frequencies that showed correlation.

Since T30 at 4 kHz was found to be of primary importance regarding the singers' perception and since correlation with T30 was found for the subjective parameters only at the 4 kHz octave band, the values obtained via regression analysis is assumed to be constant across all the middle and high frequencies.

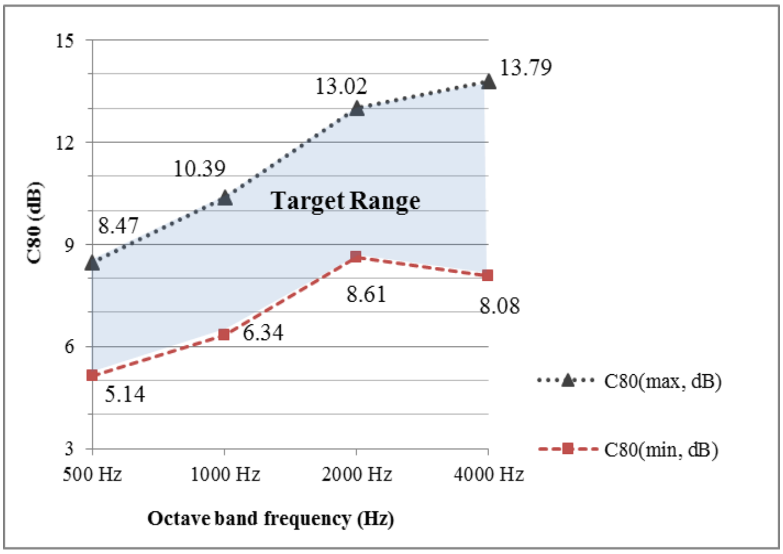

Figure 4: Target range corresponding to singers' preferred ratings for C80 room parameter

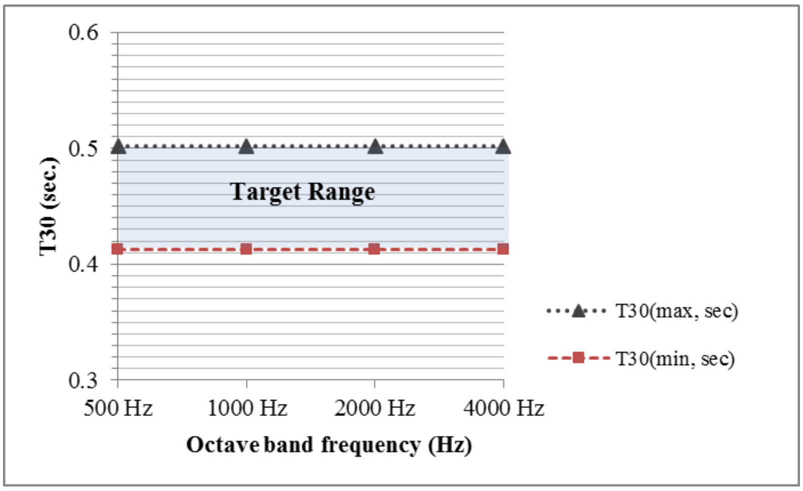

Figure 5: Target range corresponding to singers' preferred ratings for T30 room parameter

Similar analysis also conducted for the subjective "Size of the Room" and "Background Noise" parameters. The results showed that a 35 m^3 practice room is rated as "sufficient" by the Opera singers whereas a 50 m^3 practice room was preferred. The research results regarding the background noise levels (unoccupied) in the practice rooms showed that the maximum acceptable noise level was found to be 42 dBA whilst 35-38 dBA range is preferred.

According to the results of the Opera singers' subjective ratings, a constant reverberation time across middle and high frequencies relevant to room volumes is recommended by the current research. This suggests a minimum size for a practice room of 35 m^3 with a reverberation time of 0.41 sec, and a maximum of 50 m^3 with a reverberation time of 0.50 sec. These design criteria are found to be in agreement with the reverberation time values relevant to room volumes suggested by all of the following standards: BB93:2015[7] both for new built and refurbished, Music accommodation in secondary schools, A design guide (2010)[8], ANSI/ASA S12.60[9] and NS8178: 2014[10].

Regarding the background noise levels, the current research suggests not to exceed 35.3 dBA noise level which corresponds to "very weak" subjective rating based on the singers' subjective data, and where this is not possible the maximum allowable limit is suggested to be 38.8 dBA which corresponds to "weak" subjective rating which both levels are found to be in the Opera singers' preferred rating range. The suggested maximum level of 35 dBA is found to be slightly higher than the suggested levels by BB93:2015 for new built practice rooms and by Music accommodation in secondary schools, A design guide (2010) which both suggests 35 dBA of maximum background noise level, whereas 38.8 dBA is found to be below the recommended maximum limit of 40 dBA for refurbished practice rooms by BB93:2015 and recommended by AS/NZS 2107:2000 as the satisfactory level. Maximum noise levels recommended by NS8178 (27-30 dBA) on the other hand is found to be significantly lower than the recommendations of the current research while the recommendation for maximum level of 45 dBA by AS/NZS 2107:2000[11] is found to be significantly higher than the recommended levels of the current research.

4. Conclusions

With the full cooperation of the Royal Academy of Music 117 Opera singers participated in the research project. The aim of the project was to provide design guidance for music practice rooms suitable for opera singers. It was found that vocal load of the Opera singers did not show any correlation with the room acoustics, however the subjective responses showed significant correlation at the >95% level. It was found that Reverberation time (T30) and Clarity Index (C80) were key room acoustic parameters that effect singers' perception of the room as well as perception of their singing effort. The new finding was that the T30 in the 4 kHz octave band was found to play a key role on singers' perception rather than the middle frequencies ($T30_{mid}$) as used in the guidance. For Clarity Index, C80, singers' perception showed correlation with all octaves bands from 500 Hz to 4 kHz. Finally, in terms of room size, in order to provide preferred ratings of Opera singers, a practice room should be between 35-50m^3 and be designed with a flat reverberation time between 0.4 and 0.5 seconds.

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