Choral singers' perception of on-stage reverberance during an Australian tour

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Abstract - Choral singers on stage may experience the acoustics of performance spaces differently to what is perceived by the conductor or the audience. The New Zealand Youth Choir (NZYC) embarked on a tour of Australia in November and December of 2022, which presented an opportunity to conduct studies on singers' response to room acoustics. The study aimed to determine the influence of stage acoustic effects on choral singers' perception. The methodology included surveying the members of the choir after performances, and conducting acoustic measurements in the stage area. Surveys for ten venues were gathered, supported by measurements of eight venues. The venues included neo-Gothic churches, multi-purpose auditoriums and the Sydney Opera House Concert Hall. Statistical analysis of the results reinforced the understanding of singer sensitivity to and preference for spaces with relatively high reverberance, with little influence by the room volume.

1 INTRODUCTION

The New Zealand Youth Choir (NZYC) toured Australia between 26 November and 15 December 2022, beginning with a farewell concert in Auckland, New Zealand. During this time, the choir performed in a range of venues ranging from large concerts halls to smaller performance spaces such as theatres, traditional churches, and multi-purpose spaces.

The tour was identified as an opportunity to conduct a research project on the acoustic stage response of singers. As the tour inherently involved a fixed group of singers performing at various venues within a short period of time, it provided the opportunity for direct comparisons by the singers.

At the time of touring, NZYC was made up of up to 44 singers between the ages of 18 and 28. Many members were pursuing or had completed undergraduate degrees in music, with a small number at postgraduate level. Most members have moderate experience in solo and/or ensemble singing at high school and community group level. Some members are pursuing professional careers in vocal or instrumental performance. Many members were pursuing studies and careers unrelated to music, such as science and engineering, law, education, and in the public sector.

The tour began in Auckland then continued to Australia and included stops in Hobart, Port Arthur, Ross, Launceston, Melbourne, Adelaide, Perth, and Sydney. The list of performance venues for which subjective and/or objective data were gathered is presented in Table 1 overleaf.

This paper examines the results in relation to measured and perceived reverberance of the performance spaces. The conclusions are part of a broader examination of the results presented in a technical report (Zhang, 2024).

Table 1 – List of performance venues and respective room volumes

Performance Venue	Abbreviation	City	Room Volume
St Matthew-in-the-City	SMC	Auckland	11200 m^3
The Farrall Centre, The Friends' School	TFC	Hobart	4350 m^3
St David's Cathedral	SDC	Hobart	6750 m^3
Ross Uniting Church	RUC	Ross	790 m^3
Holy Trinity Anglican Church	HTA	Launceston	5400 m^3
St Paul's Cathedral	SPC	Melbourne	23300 m^3
Ian Roach Hall, Scotch College	IRH	Melbourne	~5000 m^3
Dorothy Pizzey Centre, St Catherine's School	DPC	Melbourne	4850 m^3
Christ Church St Laurence	CSL	Sydney	4600 m^3
Sydney Opera House, Concert Hall	SOH	Sydney	24500 m^3

2 RELEVANT LITERATURE

Acoustic knowledge of performance spaces for classical music has become an established area of academic and practical knowledge over the last few decades. Most of this knowledge is focused on optimising the experience of a listener sitting in the audience, and some has been on stage acoustics. However, much of this research has been undertaken focussing on instrumentalists as the performer, rather than singers.

Much of the establishing work on musician response was conducted in the 1980s by the likes of Gade (1989b) on stage support and Barron (1988) on subjective response. Many of these studies and those that followed were inspired by a paper published by Marshall et al. (1978) on the 'Acoustical conditions preferred for ensemble'.

Panton (2017) completed her doctorate research programme on the stage acoustics as experienced by classical instrumentalists in chamber orchestras. It included investigations on eight Australian concert halls, the methodology of which has influenced this project.

One of the earliest studies on vocal ensembles was undertaken by Marshall & Meyer (1985) on 'The directivity and auditory impressions of singers.' In contrast to the conclusions in the Marshall et al. (1978) paper in support for early reflections, it was found that reverberation was of greater importance to the singers compared to instrumentalists.

Fischinger et al. (2015) conducted a study with a choir using virtual room acoustics, which showed a preference for a reverberation time of 1.77 seconds over 0.0 seconds (bypass) and 4.79 seconds when singing Bruckner's *Locus Iste*.

3 METHODOLOGY

There are two components to the study: a subjective questionnaire for the musicians, and objective acoustic measurements.

3.1 Singer Questionnaire

The questionnaire aims to get an overall impression of the individual's response to the space, and was formulated with influence from similar surveys by Panton (2017) and Sanders (2002). Both questionnaires use semantic differential scales, which present pairs of opposite adjectives at the extreme ends of each scale. These studies were both influenced by Gade's (1989a) investigations into important subjective acoustics factors for orchestral musicians on stage. Further research is required to determine whether there are subjective parameters specific to singers in unamplified vocal ensembles. The questionnaire was made available in physical and PDF formats, and a Google Form.

A list of the subjective metrics and abbreviations discussed in this paper is summarised in Table 2. Refer to the project technical report (Zhang, 2024) for discussion on ease of hearing self, support, ensemble, timbre and dynamic range. These were found to have much weaker correlation to measured room reverberation, and have been omitted from the scope of this paper.

Table 2 – List of subjective metrics and abbreviations

Subjective Metric	Abbreviation	Semantic Scale		
Overall Acoustic Impression	OAI	Very unsatisfying performance experience	0 1 2 3 4 5 6 7 8 9 10	Very rewarding performance experience
Reverberance	Rev	Dry	Live 0 1 2 3 4 5 6 7 8 9 10	Overly Reverberant
Clarity	Cla	Muddy	0 1 2 3 4 5 6 7 8 9 10	Clear
Visual Impression	Vis	Unsightly/repellent	0 1 2 3 4 5 6 7 8 9 10	Gratifying

3.2 Room Acoustic Measurements

To gather acoustic data from each of the venues, the frequency response was measured at various source and receiver locations across the "stage." For this project, this is defined as the area which the choir occupied during the performances.

The measurements taken were 3D Room Impulse Responses (3DRIR) in general accordance with the procedures in ISO 3382-1:2009 *Acoustics — Measurement of room acoustic parameters — Part 1: Performance spaces* (International Organization for Standardization, 2009), using a swept-sine signal.

The hardware used was the "IRIS Mini" kit developed and tested by Marshall Day Acoustics (Dunn, 2021). This system uses a Bose Soundlink Revolve+ II Bluetooth speaker (Figure 1), Zoom H3-VR audio receiver (Figure 2) and wireless receivers, and has significant portability benefits over traditional methods. These were important factors to consider due to the logistics of international touring. The main disadvantage of using the system was that the speaker occasionally could not generate sufficient sound energy at the low frequencies to allow for good signal-to-noise ratio.

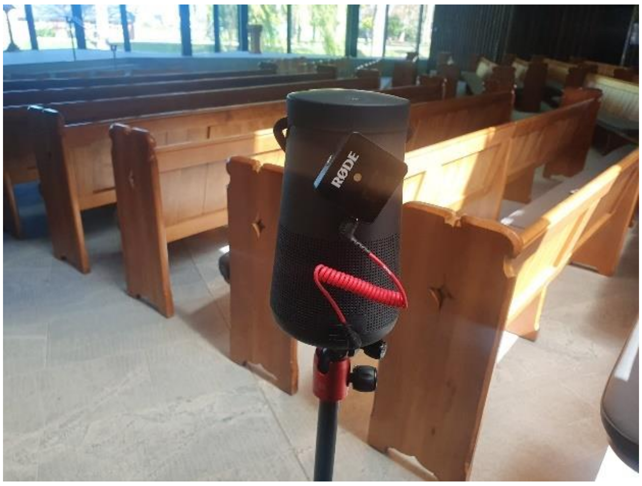

Figure 1 – IRIS Mini kit Bose Soundlink Revolve+ II source

Figure 2 – IRIS Mini kit Zoom H3-VR receiver

The source and receiver heights were generally at 1.5 ± 0.1 metres from the stage, relative to either the floor or the choir riser. This may be considered an approximation of average mouth and ear height of the singers.

Photos of the venues are shown in Figure 3 to Figure 12 overleaf.

Figure 3 – St Matthew-in-the-City (SMC)

Figure 4 – The Farrall Centre (TFC)

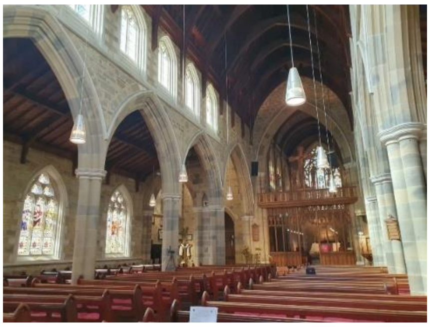

Figure 5 – St David's Cathedral (SDC)

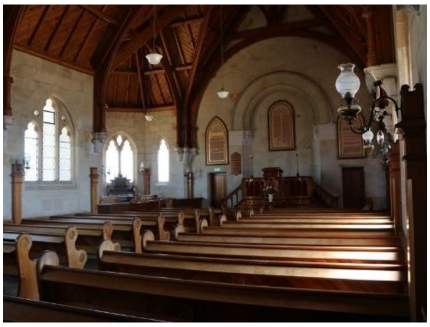

Figure 6 – Ross Uniting Church (RUC)

Figure 7 – Holy Trinity Anglican Church (HTA)

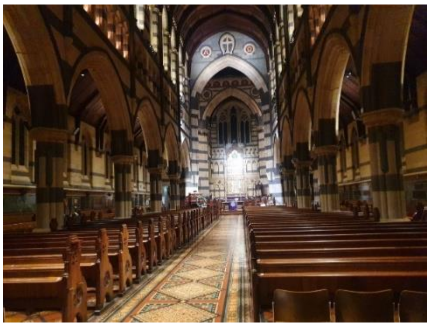

Figure 8 – St Paul's Cathedral (SPC)

Figure 9 – Ian Roach Hall (IRH)

Figure 10 – Dorothy Pizzey Centre (DPC)

Figure 11 – Christ Church St Laurence (CSL)

Figure 12 – Sydney Opera House (SOH)

4 RESULTS AND DISCUSSION

4.1 Statistical Analysis

The results were analysed using the Spearman rank-order correlation, which tests for evidence of a monotonic relationship. The Spearman correlation coefficient r_s indicates the strength and direction of the monotonic relationship of two variables. The magnitude indicates the strength, and the sign indicates the direction. The strength of the relationship can be graded using the ranges shown in Table 3. The Spearman correlation was chosen over other statistical methods such as Pearson product-moment and regression models, which test for strength and direction of linearity.

The null hypothesis is that there is no significant correlation between the subjective variables. The data has been analysed with a confidence level of 95% (or p-value < 0.05) to reject the null hypothesis.

Table 3: Grading of Spearman correlation coefficients

Range of correlation $\lvert r_s \rvert$	Strength of monotonic relationship
0.00 to 0.19	None to very weak
0.20 to 0.39	Weak
0.40 to 0.59	Moderate
0.60 to 0.79	Strong
0.80 to 1.00	Very strong

4.2 Subjective Data results

The calculated Spearman correlation coefficients are summarised in Table 4, with the strength of correlation colour-coded according to the ranges in Table 3. Correlations with p-values greater than 0.05 have been assigned no correlation.

Table 4: Spearman correlation coefficients within subjective metrics

r_s	OAI	Rev	Cla	Vis
OAI	1	0.37	0.23	0.56
Rev		1	–0.09	0.34
Cla			1	0.11
Vis				1

A selection of correlations has been plotted as a scatterplot with a locally estimated scatterplot smoothing (LOESS) line applied. To increase the definition in the density of the plots, the points have been "jittered" within a bin width of 1. The shaded areas around the LOESS fit line represent its 95% confidence interval.

Interestingly, the strongest correlation is observed between Overall Acoustic Impression (OAI) and Visual Impression (Vis) (Figure 13). This was expected in the sample of venues, as the top-rated venues for OAI were either purpose-built music venues (IRH & SOH) or historic church buildings (SMC, HTA, SPC & CSL). These spaces are typically designed to be architecturally impressive and are spaces which prioritise acoustic response for music. The school multi-purpose auditorium DPC rated the lowest in both OAI and Vis, and it is noted that the space also doubles as a gymnasium

Rev is most strongly correlated with OAI (Figure 14). However, interrogation of the scatterplot shows a flattening of the OAI rating at Rev ratings above 6. This indicates that higher reverberance is generally preferred but suggests that there was no material benefit to overall impressions once the reverberance reached a certain level. It is also possible that reverberation time above a certain level is difficult to discern.

It was anticipated that there would be a negative correlation of Clarity (Cla) and Reverberance (Rev) (Figure 15), but there was no statistical evidence to support a monotonic relationship. This suggests that there were potentially no “overly reverberant” venues, and thus no venues for which the respondents felt particularly strongly on the reduction in clarity. There is some evidence of this when observing the scatterplot above Rev ratings of 6. However, more data for venues with longer reverberation times would likely show a different trend.

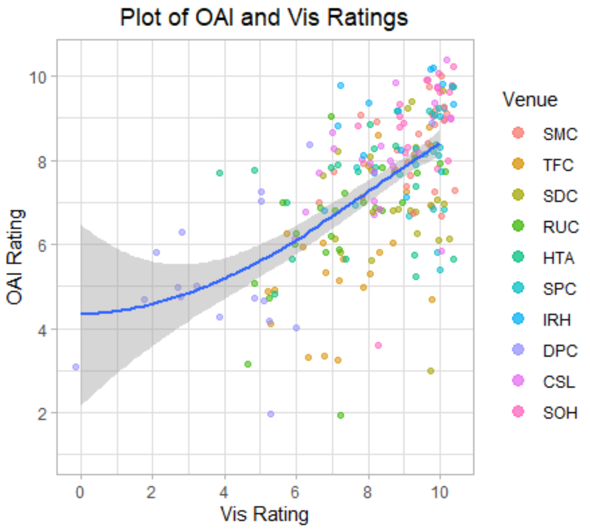

Figure 13 – Scatterplot of OAI and Vis, r_s = 0.56

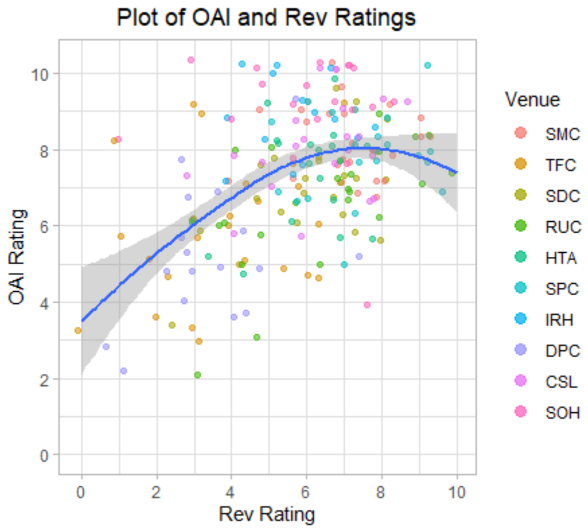

Figure 14 – Scatterplot of OAI and Rev, r_s = 0.37

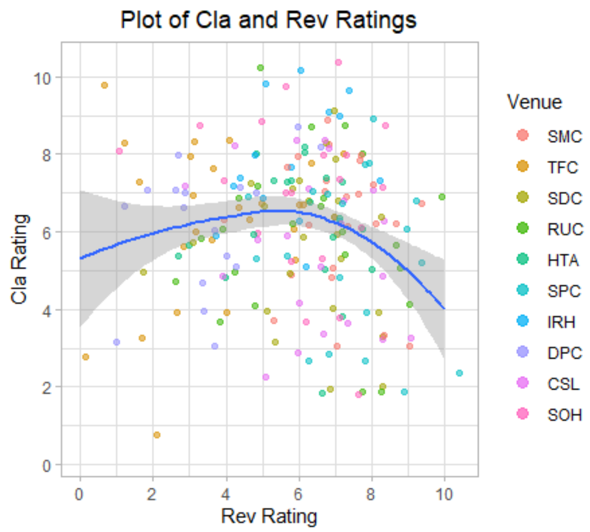

Figure 15 – Scatterplot of Cla and Rev, r_s = –0.09

4.3 Room Measurement Results

The 3DRIR measurements were analysed with the software package IRIS 2.0. Measurements at all stage positions were averaged, except for the clarity metrics for which the 1-metre source-distance and cross-stage measurements results were averaged separately. The time-based metrics (EDT, T_{30}) metrics have been arithmetically averaged, and energy-based (ST_{Early} & ST_{Late}) metrics have been logarithmically averaged.

The mid-frequency value results are presented in Table 5 overleaf. These values have been used for further statistical analysis as discussed in Section 4.4.

It is generally understood when considering reverberation time (RT) in a larger volume, that the perceived reverberance would be lower when considering the same RT in a smaller room. It would be expected that subjective reverberance would be influenced by correcting RT with volume, and a "volume-corrected reverberance" $T_{30}/\log_{10}V$ has been calculated for purposes of comparison.

The RTs were plotted against volumes with a logarithmic x-axis (Figure 16 overleaf).

Table 5 – Measured and calculated mid-frequency averaged values of acoustic metrics for each venue

	SMC	TFC	SDC	RUC	HTA	SPC	DPC	CSL
Measured parameters:								
EDT (s)	2.28	1.50	1.53	1.57	1.86	1.81	1.20	2.37
T_{30} (s)	2.63	1.38	1.95	1.62	1.81	2.33	1.60	2.49
ST_{Early} (dB)	-13.1	-10.7	-13.0	-6.1	-13.5	-13.5	-9.1	-10.9
ST_{Late} (dB) [1]	-12.3	-12.2	-12.8	-7.8	-13.5	-14.9	–	-10.1
Calculated parameter:								
$T_{30}/\log_{10}V$ ($s/\log_{10}m^3$)	0.65	0.38	0.51	0.56	0.49	0.53	0.43	0.68

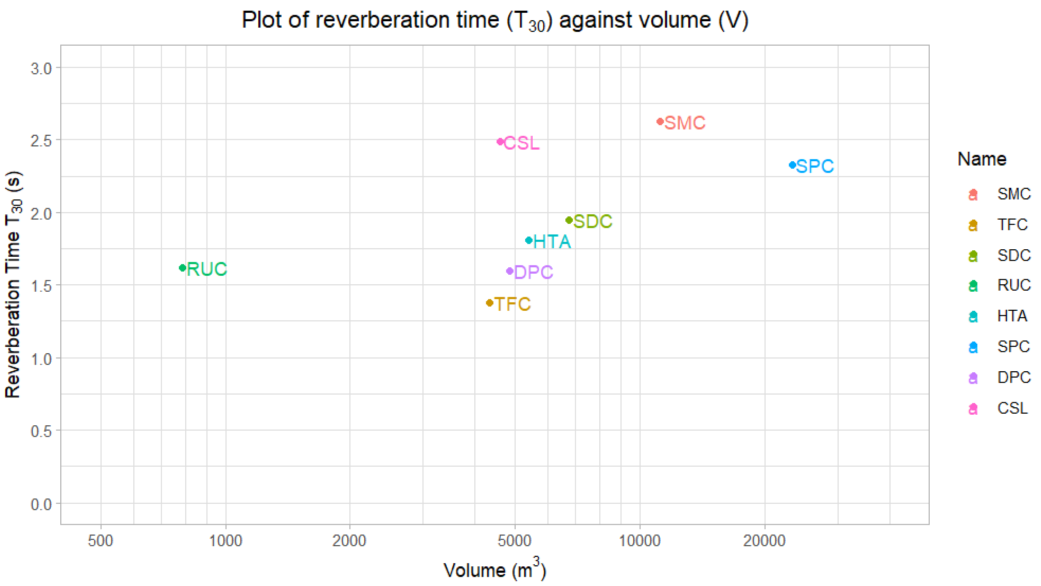

Figure 16 – Plot of reverberation time against volume of measured venues

Unfortunately, concert logistics did not allow for measurements to be taken at IRH and SOH. The acoustician Jordan, who was involved in the original design of the Sydney Opera House Concert Hall, measured that the mid-frequency EDT was approximately 2.5 seconds unoccupied (1973). The Concert Hall acoustic refurbishment that was completed in mid-2022 mainly focused on the overhead reflectors and the stage-side diffusers. This likely changed the characteristics of the early reflections on the stage, but are unlikely to have significantly changed the reverberation time.

4.4 Subjective and Objective Correlation

Similar to the subjective data, a Spearman correlation was conducted on the subjective and objective data to determine how accurate or sensitive the singers could be in discerning actual room response. The analysis is based on the questionnaire data and the averaged acoustic measurements as summarised in Table 5.

The Spearman correlation coefficients (r_s) are summarised in Figure 6 overleaf and graded in accordance with the criteria in Table 3.

[1] ST_{Late} for DPC could not be measured reliably and has been excluded from the analysis.

Table 6 – Spearman correlation coefficients of subjective and objective measures

r_S	OAI	Rev	Cla	Vis
EDT	0.51	0.47	–0.07	0.38
T_{30}	0.53	0.53	–0.08	0.50
$T_{30}/\log_{10}V$	0.43	0.49	–0.09	0.32
ST_{Early}	–0.38	–0.34	0.04	–0.44
ST_{Late}	–0.16	–0.18	0.03	–0.34

A selection of correlations has been plotted as a scatterplot with boxplot and a locally estimated scatterplot smoothing (LOESS) line applied. To increase the definition in the density of the responses, the points have been "jittered". The shaded areas around the LOESS fit line represent its 95% confidence interval. Note that the boxplot outlier points have been removed to avoid visual confusion with the jittered datapoints.

The reverberation time metrics, in particular T_{30}, has the strongest correlation with Rev (Figure 17). This indicates that the respondents were able perceive the difference in reverberance between the venues with the greatest consistency compared with other metrics (r_S = 0.53).

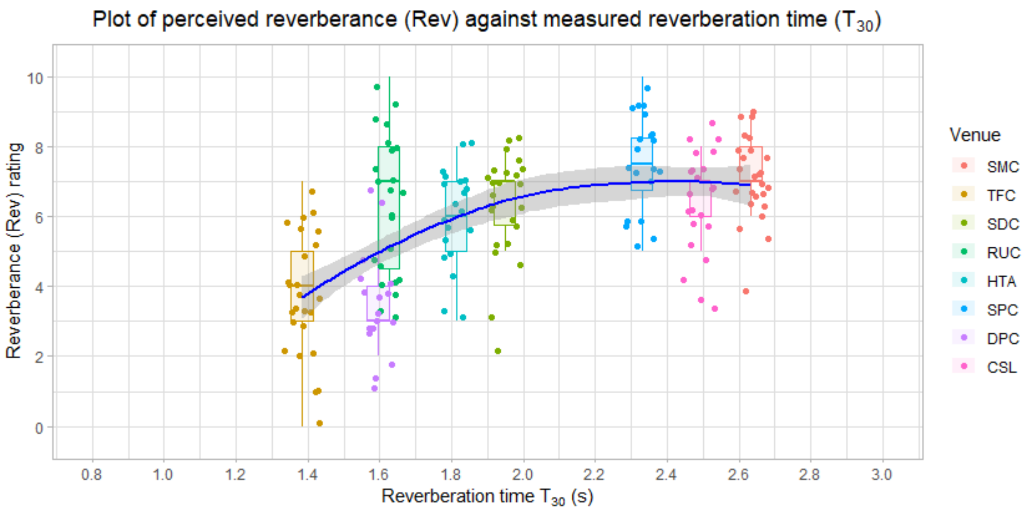

Figure 17 – Scatterplot with boxplot of Rev vs. T_{30}, r_S = 0.53

For the venues without RT measurements, it is also noted that the approximate reverberation time of SOH (2.1–2.5 seconds before refurbishment) and its Rev rating (6.5) falls somewhat within the LOESS fit confidence margin. The plot indicates that the reverberation time for IRH may fall within the range 1.7–2.0 seconds, and the author attests that this was likely the case.

At higher reverberation times above 2.0 seconds, there appears to be flattening of the LOESS fit line which settles at around a Rev rating of 7. With reference to the semantic differential scale for Rev, this indicates that there were no venues which the respondents deemed "overly reverberant." In combination with the OAI rating, it implies that there may be a range of reverberation times, such as 2.2–2.6 seconds, which may be judged as "ideal" by this specific tour choir. However, it is worth noting that the first performance of the tour was at SMC, which had the longest measured reverberation time across the venues. It is possible that the Rev rating of the other venues may have been affected by relating them to the venues earlier in the tour.

There may be a reverberation time for which the median Rev rating may start to tend towards "overly reverberant." This is suggested in the study by Fischinger et al. (2015) in which a space with a shorter reverberation time of 1.77 seconds was preferred over 4.79 seconds by the singers. There are limited controlled studies in which a range of reverberation times greater than 3 seconds are investigated. However, it is likely that reverberation times greater than this would restrict the repertoire to pieces with slower tempi, and with less requirements for clarity of consonants.

Notably, the strength of the reverberation time correlation is slightly weakened when room volume is accounted for (r_s = 0.49). This indicates that the singers' perception of reverberance was not significantly affected by the volume of the space. However, this may be relevant for outlier cases such as RUC with the smallest room volume, as the median reverberance rating is within the LOESS fit confidence margin (Figure 18).

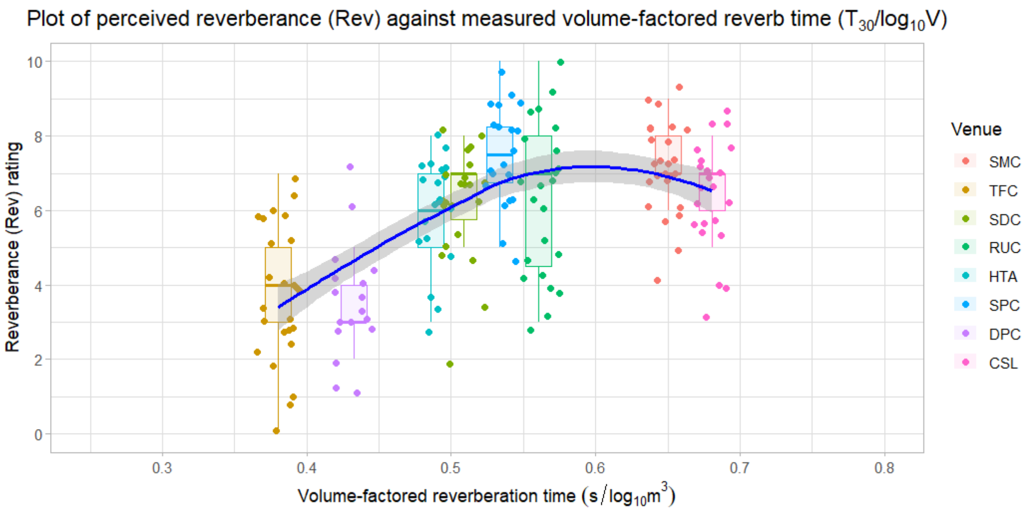

Figure 18 – Scatterplot with boxplot of Rev vs. $T_{30}/log_{10}V$, r_s = 0.49

The reverberation time metrics had a comparably strong correlation with OAI (Figure 19). The results support Marshall and Meyer's findings which indicate that singers respond primarily to reverberation as opposed to other acoustic aspects such as early reflections (1985).

The unmeasured IRH and SOH venues both had the highest median ratings of 9.0 for OAI, with a high level of agreeance. The trend in Figure 19 implies that these venues would have reverberation times above 2.5 seconds, more reverberant than most measured venues. However, the author estimates that the reverberation times of the IRH and SOH to be in the range 2.0–2.5 seconds. If measured and added to the analysis, these venues would likely affect the apparent linearity of the trend.

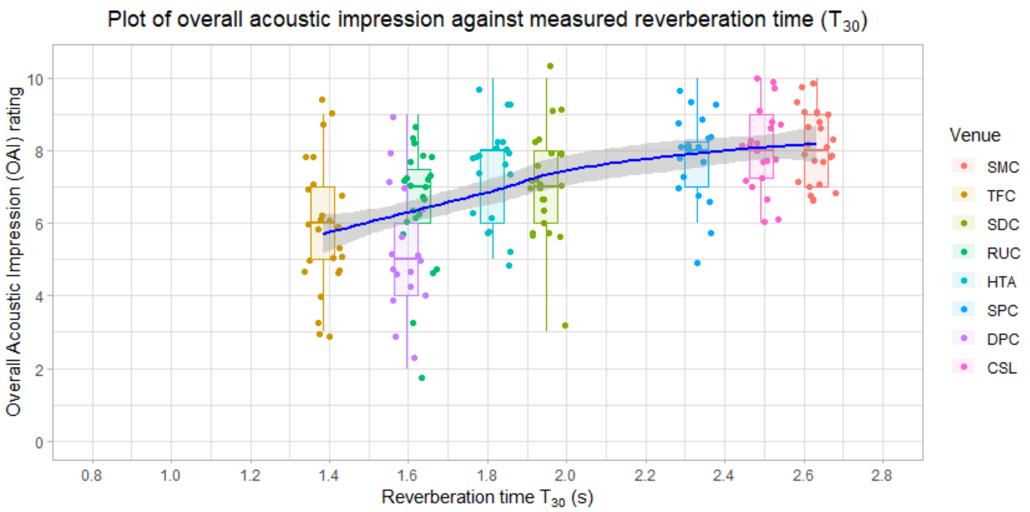

Figure 19 – Scatterplot with boxplot of OAI vs. T_{30}, r_s = 0.53 (jitter bin width of 0.05, LOESS fit span of 1)

5 CONCLUSIONS

Across the study, the results indicate that no venue was considered "overly reverberant," and venues with higher reverberation times were preferred. Negative effects on clarity were not significant in the sample of venues. Venues which were rated for best overall acoustic impression also had better visual impression.

Spaces which were measured to have reverberation times of 2.2–2.6 seconds were most preferred by the singers. The singers were also able to perceive the difference in reverberation times with good relative precision ($r_s = 0.53$), and this was generally not significantly affected by room volume for spaces larger than 3500 m^3. Given the little to no negative statistical correlation of reverberation time to clarity, this range of preferred reverberation times presents an acceptable level of loss in clarity.

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