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Overview and preliminary results from a study of stage acoustics for chamber orchestras

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Abstract

This paper describes an ongoing project that examines the on-stage acoustic conditions of major Australia purpose-built concert halls in relation to their use for chamber music performance. During a national tour in 2015, members of the Australian Chamber Orchestra made subjective assessments. Acoustic measurements in these auditoria are being undertaken using the same stage configuration as the performances, with both a traditional omnidirectional receiver and with a 32-channel spherical microphone array (Eigenmike). At the time of writing, measurements have been completed in six halls. This paper presents these initial results and considers both traditional omnidirectional parameters and also the spatial response on stage in the auditoria. The results of the subjective study have been previously reported, but are summarized briefly and then discussed in this paper in relation to the objective measurements. Further auditorium measurements are planned; nevertheless, these early results indicate some notable and interesting relationships between the objective measurements and subjective musician assessments.

Keywords: stage acoustics, musicians, chamber music,

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1 Introduction

Past work into auditorium acoustics from the perspective of musicians has primarily focused on symphony orchestras and has been especially concerned with the analysis of impulse responses measured on stage with an omnidirectional receiver and omnidirectional source. Contributions from Gade [1], and more recently Dammerud [2], have resulted in several omnidirectional stage parameters that may be used to assess the acoustic conditions on stage for a symphony orchestra.

Gade's work focused on the 'support measures' [1]. The support measures (ST_{early} and ST_{late}) are measured with a 1 m source-receiver distance at several locations on stage and then arithmetically averaged. These measures are derived from energy arriving in different time intervals relative to that of the direct sound. ST_{early} is defined to assess the energy of reflections arriving between 20-100 ms, whereas ST_{late} is defined to assess the reflections between 100-1000 ms. These parameters are included in ISO 3382.1 [3]. The integration limits broadly aim to separate direct sound, first order reflections and later reflections.

Dammerud focused on across-stage measurements (in addition to the 1 m source-receiver distance measurements) and examined the following measures: T_{30}, EDT, C_{80}, $G_{7\text{-}50}$, G_e $(G_{0\text{-}80})$ and G_l $(G_{80\text{-}inf})$, as well as ratios based on stage dimensions. The parameters T_{30} and EDT measure the rate of decay of sound; T_{30} is defined as twice the time taken for 30 dB of decay, whereas EDT is defined as six times the time taken for the initial 10 dB of decay, see [3]. C_{80} is an energy ratio of sound arriving before 80 ms to sound arriving after 80 ms, also defined in [3]. $G_{7\text{-}50}$, G_e and G_l are variations on sound strength G (which is defined in [3]); $G_{7\text{-}50}$ integrates between 7 and 50 ms, where G_e includes all sound energy before 80 ms, and G_l includes all sound energy arriving after 80ms.

Dammerud's project concluded that the direction from which early reflections arrive is subjectively important to musicians [2]. However, assessing the directionality of sound arriving on stage is difficult with a conventional omnidirectional source and receiver. In more recent work, Guthrie used a spherical microphone array (analysed in terms of 2nd order spherical harmonics) for measurements on stages, and examined the subjective significance of acoustic parameters defined spatially, as well as temporally [4]. This was done with musicians preforming in the laboratory with synthetic sound fields. Guthrie examined the directional distribution of many common acoustic parameters including G, $LQ_{7\text{-}40}$ and the ST measures.

In the present work, a spherical microphone array with 32 individual transducers has been used for on-stage measurements. This opens up the possibility of examining the directionality of on-stage fields with 4th order ambisonics. Another difference to the previous studies mentioned is that chamber orchestras have been the focus. Chamber orchestras generally consist of fewer than thirty players; however, as they often play without the aid of a conductor their acoustical needs are arguably at least as critical. As part of this project, the Australian Chamber Orchestra

(ACO) has provided subjective assessments of Australian auditoria. This paper outlines the in-situ measurement procedure on stage in auditoria, and presents initial results, focusing on omnidirectional parameters as well spatially defined acoustic parameters. A brief overview of the musician surveying procedure and results is also provided.

2 Subjective assessment of auditoria

A questionnaire completed by musicians to the Australian Chamber Orchestra (ACO) covered the key aspects of subjective acoustical experience of musicians playing on-stage, including: Overall Acoustic Impression (OAI), Hearing Self (HS), Support (Sup), Ensemble (Ens), Reverberance (Rev), Clarity (Cl), Warmth (War), Timbre (Tim), Communication with the Main Auditorium (Com) and Echoes (Ech). Visual Impression (VI) was also included on the questionnaire. Additionally, the questionnaire included a section for written comments. The questionnaire was administered in conjunction with a tour of the orchestra – the musicians completing the questionnaire would have been familiar with the auditoria, and additionally would have completed the questionnaire shortly after rehearsing/performing in the auditorium. Each musician completed a separate questionnaire in each auditorium on the tour; however, all the questionnaires completed by an individual musician could be linked to examine individual musician trends as required. There was a response rate of 68% from the ACO. An overview of the results from this surveying has been included in previous work by the authors [5]; it will be summarized briefly in this paper for the purpose of comparison with the objective acoustic measurements. The auditoria visited by ACO were Perth Concert Hall (PH), Adelaide Town Hall (AH), Sydney City Recital Hall Angel Place (AP), Llewellyn Hall Canberra (LH), Hamer Hall Melbourne (HH), Sydney Opera House Concert Hall (SO), Wollongong Town Hall (WH), and QPAC – Queensland Performing Arts Centre Brisbane (QC).

3 On-stage measurements in auditoria

In this study 1 m measurements were taken at the four locations on stage shown in Figure 1, and across-stage measurements were also taken (with source-receiver distances between 2.7 m and 6 m). An omnidirectional source (B&K omnidirectional loudspeaker type 4295) was used; for the receiver a spherical microphone array (type EM32 Eigenmike) was used and in four auditoria an omnidirectional receiver (B&K omnidirectional receiver type 2669) was used for comparison.

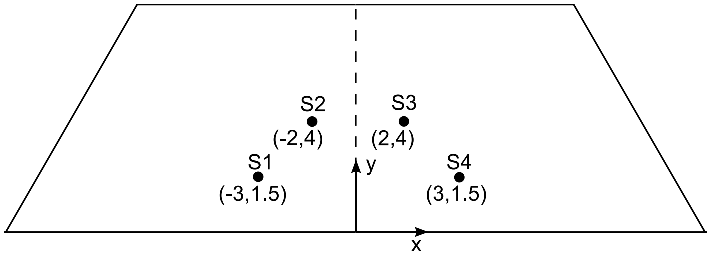

Figure 1: On stage source (and receiver) locations. The coordinate system is located at the center front of stage, units are metres.

The measurements were undertaken in unoccupied auditoria, and on-stage without musicians or stage furniture present. This is in line with the recommendation from Gade to undertake stage measurement on smaller stages, or stages used for chamber music, without any furniture present [1].

a) PH

b) AH

c) AP

d) LH

e) SO

f) WH

Figure 2: Stages visited to undertake acoustic measurements

Around each of the source positions in Figure 1 four 1 m measurements were taken (in positions front, back, left and right in relation to the stage orientation). The heights of the source and receiver were 1.5 m, chosen because the orchestra members mostly stand to play.

Additionally, 12 across-stage measurements were undertaken between the four source positions. Stage acoustic conditions were matched to those used during performances by ACO, except due to availability in AH a slightly smaller stage extension was used than the stage extension used during the ACO performance. Figure 2 provides a photo of each stage acoustically measured in the study. For reference stage dimensions are included in Table 1.

Table 1: Auditoria and stage dimensions

Auditorium	Stage height (m)	Stage width front (m)	Stage depth (m)
PH	16.5	18.22	11.1
AH	11.4	17	7.3*
AP	12	13	9.2*
LH	9.8	19.5	8*
SO	22#	20.5	11.51
WH	5.8	12	7.1*

*indicates a stage extension or adjustable stage depth is used in this auditorium (the ACO setting is given).
#height to cloud reflectors in SO was approximately 9 m.

Table 2: The average orchestra subjective scores (out of 10) and the standard deviation for the auditoria in the study for a set of 'key' subjective scales

	Subjective Scales				
Auditoria	*OAI*	*Sup*	*Ens*	*Rev*	*Tim*
PH	8.8 ± 1.0	8.9 ± 1.9	7.7 ± 1.0	6.1 ± 1.0	8.3 ± 1.2
AH	8.4 ± 1.1	7.7 ± 1.7	7.2 ± 1.3	7.3 ± 1.3	8.4 ± 1.2
AP	7.8 ± 1.4	7.2 ± 2.1	7.7 ± 1.2	6.1 ± 1.2	6.5 ± 2.2
LH	6.3 ± 1.9	6.0 ± 2.3	5.1 ± 1.5	5.7 ± 1.5	6.5 ± 1.3
HH	6.2 ± 1.9	5.8 ± 1.9	6.0 ± 1.4	5.6 ± 1.4	6.4 ± 1.5
SO	5.9 ± 1.5	5.0 ± 2.2	5.4 ± 1.4	5.5 ± 1.4	6.2 ± 1.3
WH	5.4 ± 1.9	5.7 ± 1.6	4.9 ± 2.6	5.9 ± 2.6	5.6 ± 1.8
QC	5.3 ± 2.3	4.5 ± 2.3	4.3 ± 2.3	5.2 ± 2.3	4.9 ± 2.1

4 Results

4.1 Orchestra questionnaire

The key subjective scales (those scales that correlated highly with overall acoustic impression (OAI)) were found to be: `Support' (r =0.73, p<0.01, N =115), Ensemble (r = 0.71, p<0.01, N=114) and Timbre (r = 0.68, p<0.01, N=111). Reverberance (Rev) is known to be a subjectively important acoustic attribute for musicians [6]; the importance of Rev was likely to be poorly observed in this dataset because there was little variation in the reverberation time in the different auditoria and values were within the range considered to be good. Therefore, the importance of adequate reverberance in venues should not be discounted. In a second study by the authors completed with ACO2 (the sister group of ACO) in non-purpose built auditoria with more variable reverberation times Reverberance was shown to be highly correlated with OAI [5]. From the subjective responses the most preferred auditorium for the ACO was PH (the favourite auditorium of 10 out of the 15 musicians), followed closely by AH, and then followed by AP. The least preferred auditoria were WH and QC. The average orchestra assessment out of 10, and the standard deviation, for the key subjective scales OAI, Support (Sup), Ensemble (Ens), Reverberance (Rev) and Timbre (Tim) are presented in Table 2. Note that unlike the other scales, the subjective scale for Rev was bipolar, with 5 as the optimal condition, 10 being over reverberant and 0 being dead/dry. The written comments from musicians also provided some interesting insights into the acoustics on stage in each auditoria, a selection of these comments is presented in Table 3.

Table 3: A selection of comments from musicians regarding on-stage acoustics in auditoria

Auditoria	Comments
PH	"*Best concert hall in Australia!*" "*Best acoustics*" "*Warm Hall! Great!*"
AH	"*I love playing in this hall*" "*Nice Hall*" "*Lovely hall to play in*" "*Good size hall. Not too big. Little bit too washy at times*"
LH	"*Feeling of playing alone – distance from other musicians is problematic. Quite cold sound also*" "*In loud passages difficult to achieve togetherness.*" "*Difficult to hear across stage – close players are overly loud.*" "*A bit distant on stage.*" "*Difficult to hear other side of the orchestra.*"
SO	"*Difficult to hear across the stage*."
WH	"*It feels very live on the stage (I get the feeling the result in the hall is better than on the stage)*" "*Very loud!*"

4.2 Objective acoustic measurements

4.2.1 Omnidirectional parameters

The omnidirectional parameters reported in this study include: ST_{early} and ST_{late} (arithmetically averaged over 250-2000 Hz), G, G_e, G_l, $G_{7\text{-}50}$, T_{30} *and EDT. G* and G_l (and to some extent also G_e and $G_{7\text{-}50}$) were notably greater in WH than in the other auditoria in the study. In Table 3, the *G* parameters are reported for the 1 kHz octave band for the 2.7 m measurements; in each case WH is much higher than the other auditoria. This trend was evident in the across-stages measurements with 4, 5.6 and 6 m source-receiver distances. Figure 3a shows this same trend visually, and includes 250–2000 Hz octave bands. WH had a relatively small stage, see Table 3. The support measures were arthimetically averaged over 250–2000 Hz and are presented in Table 5 and Figure 3b. The auditorium that appears most different is WH: like the *G* parameters, it has far higher values of ST_{early} and ST_{late} than the other auditoria included in the study. T_{30} and EDT averaged over 250–500 Hz and averaged over 1-2 kHz are presented in Table 6. Little variation in these reverberation parameters is observed between auditoria. This concurs with the minimal variation noted in subjective reverberance (Table 1). The average orchestra assessments for Rev (on a scale from 0-10) are in the range 5 - 6.1 for all auditoria, with the exception of AH, which was only slightly higher at 7.3, and shows the highest T_{30}. The fact that T_{30} for SO was next highest, in spite of a low score on Rev, is most likely due to its large size.

Table 4: Power average 1 kHz octave band *G* parameters for 2.7 m source-receiver distance

		1 kHz octave band					
Parameter	**Meas. dist. (m)**	**PH**	**AH**	**AP**	**LH**	**SO**	**WH**
G (dB)	2.7	14.37	15.08	15.40	14.18	13.36	17.78
$G_{7\text{-}50}$ (dB)	2.7	7.87	9.35	9.34	5.59	4.42	12.46
G_e (dB)	2.7	13.57	11.29	14.71	13.51	13.42	16.31
G_l (dB)	2.7	6.62	8.58	6.87	5.75	6.03	12.18

Table 5: The *ST* measures, arithmetically averaged over 250-2000 Hz and over 4 source positions

		Average 250 - 500 Hz					
Parameter	**Meas. dist. (m)**	**PH**	**AH**	**AP**	**LH**	**SO**	**WH**
ST_{early} (dB)	1	-14.60	-11.99	-11.80	-13.81	-14.30	-6.30
ST_{late} (dB)	1	-13.55	-11.87	-13.49	-14.05	-15.18	-8.95

Table 6: Reverberation Time and Early Decay Time on stage

		Average 250 - 500 Hz octave band					
Parameter	**Meas. dist. (m)**	**PH**	**AH**	**AP**	**LH**	**SO**	**WH**
T_{30} (s)	> 2.7 m	1.84	2.11	1.86	1.95	2.00	1.82
EDT (s)	> 2.7 m	1.51	2.04	1.40	1.75	2.00	1.40
		Average 1 - 2 kHz octave band					
T_{30} (s)	> 2.7 m	2.01	1.91	1.92	1.89	2.36	1.90
EDT (s)	> 2.7 m	1.72	1.91	1.41	1.71	2.36	1.39

4.2.2 Spatially defined parameters

Using the spherical microphone array Eigenmike for stage measurement also allowed spatially defined acoustic parameters to be investigated (i.e. considering the directionality of the on-stage sound field). Previous work from Dammerud has indicated that symphony orchestra musicians have a preference for high and narrow stage enclosures [2]. Dammerud relied on physical dimensions of stages to demonstrate this trend; however, in this paper a spatially defined acoustic parameter is used to investigate whether a similar preference is observed when surveying chamber orchestra musicians. In previous work with spherical microphone arrays, Guthrie found a spatial ratio of $LQ_{7\text{-}40}$ from 'top/sides' was relevant for musician playing in ensemble conditions (decreasing values were preferred) [4]. However she only used 2nd order ambisonics.

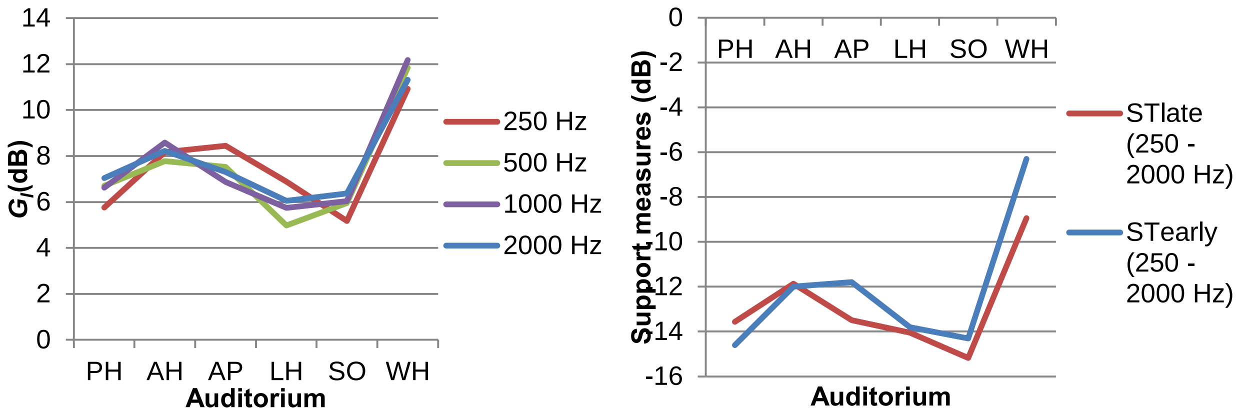

Figure 3: Omnidirectional parameters measured on stage. Left: Power average *G*$_l$ with source-receiver distance of 2.7 m. Right: Arithmetic average of *ST* measures with 1 m source-receiver distance over 250 - 2000 Hz octave bands. Auditoria as listed in Section 2.

Based on this previous work by Dammerud and Guthrie a 'top/sides' ratio, defined to capture early energy was investigated in this paper. The upper integration time limit of 50 ms was selected to capture 'early' reflections, i.e. a total return reflection path of under 17 m. Traditionally 100 ms has been used as the upper limit for the arrival of early reflections (such as in the support parameters proposed by [1]). However, based on work by Guthrie and Dammerud it appears very early arriving reflections (i.e. before 40 or 50 ms) are highly relevant for ensemble playing conditions [4] [2]; also we are interested in whether first order reflections from 'sides' arrive before or after those from the 'top' region. A spatial ratio of 'top' relative to 'sides' TS_{20-50} was defined as

$$TS_{20-50} = 10\log\frac{\int_{20ms}^{50ms} p^2(t)_{TOP}\,.dt}{\int_{20ms}^{50ms} p^2(t)_{SIDES}\,.dt}. \qquad (1)$$

Fourth order ambisonics analysis was used to isolate sound pressure from the top (p_{top}) and sound pressure from the sides (p_{sides}) as well as bottom, front and back; top and sides are defined relative to the orientation of the stage (note, sides includes sound pressure from the left and right of the stage). This work is described in more detail in [7]. The $TS_{20\text{-}50}$ parameter was derived from the on-stage 1 m source-receiver measurements. The parameter was found as an average value of the four measurements around the source. In Figure 5a the results are presented for source position S1; the auditoria are plotted from left to right in terms of the musicians' most preferred to least preferred auditorium (i.e. PH is the most preferred auditorium and WH is the least preferred auditorium). We see that the trend of decreasing $TS_{20\text{-}50}$ being preferred is clearly observed in our dataset. The same results for source position S3 are shown in Figure 5b, and similar trends were observed for the average of the 1 m measurements at S2 and S4. The method of averaging 1 m measurements on stage is in line with procedure used for the *ST* parameters; however, it may also be of interest to investigate the 'across stage' measurements (with larger source-receiver distances) when considering ensemble playing.

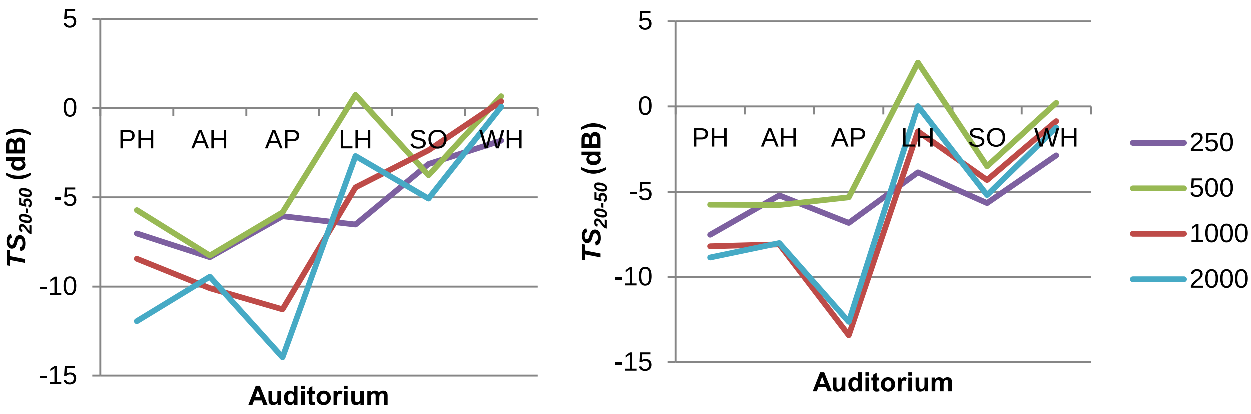

Figure 5: Average TS_{20-50} (dB) for the four 1 m source-receiver distances for 250 – 2000 Hz octave bands, left: around source position S1, right: around source position S3.

5 Discussion

Musicians commented that the sound on-stage in WH was "too live" or "very loud". This is also observed in the objective data as indicated by G, G_e and G_l parameters on-stage, which are far higher in WH than in other auditoria in the study. WH was also one of the least preferred auditoria in the study. It is also noted that ST_{early} is usually between -10 and -15 dB in the auditoria (with the exception of WH). Gade's suggested optimum value of ST_{early} is -10dB for chamber music and -14dB for symphony music [8]. Therefore WH is the only venue which is clearly outside the suggested optimum range for support, and this is reflected in the musicians' feedback. However, it is also evident that the support measures are unable to distinguish the other six auditoria from one another – even though musician feedback clearly indicates there are distinct differences in the different stages/auditoria in terms of overall acoustic impression and ensemble. There was minimal variation observed in reverberation time (T_{30}) in the auditoria, and correspondingly the musicians' ratings indicated that subjectively there was little variation in reverberance. This was not the case for other key subjective criteria, such as ensemble and support. Musicians' comments revealed that issues with ensemble were particularly relevant to their experience in some auditoria (for example "*Difficult to hear across stage – close players are overly loud"* regarding LH).

A spatially defined parameter TS_{20-50} has been proposed by the authors and was used to investigate the ratio of early energy arriving from above relative to that arriving from the sides. It appears that lower values of this parameter are preferred; indicating more early sound from the sides relative to the top is preferred for chamber orchestra musicians playing in ensemble. Further work may indicate whether strength or timing of the top and sides early reflections is more important. This finding agrees with the previous findings for symphony orchestras of Dammerud [2] and Guthrie [4]. This is a preliminary finding, which will be investigated further with more musician surveying and on-stage acoustic measurements. Given the limited data available so far (a total of six data points) attempts have not been made at more sophisticated statistical analysis of the data (e.g. mixed-model or regression analysis). Following the completion of more stage measurements a comprehensive analysis of the data will be conducted, accounting for individual musician trends, and more thoroughly examining potential preferred ranges for the on-stage acoustic parameters.

6 Conclusions

In this study on-stage acoustic measurements have been completed in six purpose-built Australian auditoria and subjective musician surveys have been conducted in these same auditoria. This is a significant study of stage acoustics focusing on chamber orchestra musicians. The initial findings indicate a spatially defined acoustic stage parameter assessing early energy from above relative to early energy from the sides may be relevant to the preferences of chamber orchestra musicians playing in ensemble. It appears lower values of such a parameter are preferred.

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