MARSHALL DAY Acoustics

INVESTIGATIONS INTO CHORAL SINGERS' PERCEPTION OF STAGE ACOUSTICS DURING AN AUSTRALIAN TOUR

SUMMARY OF RESEARCH OUTCOMES

Rp 001 20220963 | 5 May 2024

MARSHALL DAY
Acoustics

84 Symonds Street
PO Box 5811
Victoria Street West
Auckland 1142 New Zealand
T: +64 9 379 7822 F: +64 9 309 3540
www.marshallday.com

Project:	**INVESTIGATIONS INTO CHORAL SINGERS' PERCEPTION OF STAGE ACOUSTICS DURING AN AUSTRALIAN TOUR**
Prepared for:	**Marshall Day Acoustics Research & Development Fund NZ Trust** **PO Box 5811** **Victoria Street West** **Auckland 1142** **New Zealand**
Report No.:	**Rp 001 20220963**

Document Control

Rev:	Comments	Date:	Author:	Reviewer:
–	For public release	5 May 2024	Maggie M. Zhang maggie.zhang@marshallday.co.nz	Malcolm Dunn

Cover Photo: © Lucas Packett Photography 2022

EXECUTIVE SUMMARY

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 chorister stage response. Similar studies have been conducted with touring orchestras and instrumental chamber groups. However, there is a gap in the existing literature for unamplified vocal ensembles.

The purpose of the study was to determine the influence of performance space stage acoustics on choral singers' perception. The study intends to build on existing understanding of the importance of reverberation to choral singers, as well as determine other aspects that affect the overall acoustic impression.

The study was conducted by surveying the members of the choir after formal performances, and conducting acoustic measurements focused on the stage response. The questionnaire comprised of a combination of responses to semantic differential scales and short-form answers. A total of 209 unique responses was gathered from the singers over 10 venues, with response rates of 33% (n=14) to 58% (n=25) across the whole choir for the venues. Measurements were conducted at eight venues, and were a mix of historical churches, multi-purpose school auditoriums and a contemporary concert hall.

The subjective and objective data across all venues was analysed using a Spearman rank-order correlation, which determines the strength of a monotonic relationship between subjective variables. The study reinforced singer sensitivity to and preference for spaces with relatively high reverberance and is consistent with the literature. However, it revealed an aversion to spaces with high levels of early sound energy, which contrast with the existing understanding of stage support for musicians. The most preferred venues were generally neo-Gothic cathedrals with high reverberation times and superior visual impression.

Compared with contemporary symphony orchestras, performance and rehearsal spaces which prioritise the acoustics for choral singers are fewer. The findings may aid acousticians and architects in their understanding or singers' requirements to design and retrofit suitable spaces for unamplified vocal ensembles. It may also aid musicians and ensemble managers in identifying suitable spaces for performances and rehearsals.

This report shall be read and printed in colour only, to enable intended interpretation of results.

This report has not been externally peer-reviewed.

Ethics Statement

This study involves human participants and adheres with the ASA Ethical Principles[1]. Informed consent was verbally obtained from all participants individually, and participation was conducted on an opt-in basis.

---

[1] Ethical Principles of the Acoustical Society of America for Research Involving Human and Non-Human Animals in Research and Publishing and Presentations acousticalsociety.org/ethical-principles

ACKNOWLEDGEMENTS

This research was supported through generous funding from the ***Marshall Day Acoustics Research & Development Fund NZ Trust***.

This study would not have been possible without the enthusiasm from the **30 singers in NZYC** who participated in the questionnaires. Many thanks for the enthusiasm and commitment.

Thank you to fellow chorister **Takerei Komene**, for their assistance on the acoustic measurements during the tour. Thank you to **Dr Yuxiao Chen** from the MDA Sydney office, for conducting the acoustic measurements in Christ Church St Laurence.

It is a privilege to have access to the wealth of knowledge at Marshall Day Acoustics. Particular thanks to **Malcolm Dunn**, **Christopher Day**, **Sir Harold Marshall** and **Peter Exton** for providing their opinions and advice on this project.

Thank you to **Daniel Protheroe** for all his development work on the IRIS software that contributed a major role in the acoustic measurements, and his ongoing support on its use and interpretation.

Thank you to **Dr Justine Hui** from the University of Auckland, for her time in discussing the statistical modelling of the data.

Thank you to **Dr Anders Christian Gade** for sharing his insight into application of the stage support parameters.

Thank you to **Louise Jakeway**, our manager for NZYC, who supported coordination of measurements and resources with each of the venues. Thank you to the music staff **David Squire**, **Morag Atchison** and **Michael Stewart** for their support and interest in the project.

Figure 1: NZYC performing *Kua Rongo* at Ian Roach Hall, Scotch College (© Lucas Packett Photography 2022)

TABLE OF CONTENTS

ACRONYMS

3DRIR	3D Room Impulse Responses
BR	Bass Ratio
CSL	Christ Church St Laurence
DPC	Dorothy Pizzey Centre
EDT	Early Decay Time
HATS	Head and Torso Simulator
HTA	Holy Trinity Anglican Church
IACC	Inter Aural Cross-Correlation
IRH	Ian Roach Hall
JND	Just Noticeable Difference
LOESS	Locally Estimated Scatterplot Smoothing
MDA	Marshall Day Acoustics
NZ	New Zealand
NZYC	New Zealand Youth Choir
OAI	Overall Acoustic Impression
RUC	Ross Uniting Church
SDC	St David's Cathedral
SMC	St Matthew-in-the-City
SOH	Sydney Opera House
SOR	Self-to-Other Ratio
SPC	St Paul's Cathedral
ST	Stage Support
TFC	The Farrall Centre
RT	Reverberation Time

1.0 INTRODUCTION

1.1 Project Background

The New Zealand Youth Choir (NZYC) toured Australia[2] between 26 November to 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 involves a fixed group of singers performing at various venues within a short period of time, it provides the opportunity for direct comparisons by the singers.

1.2 Aims and Desired Outcomes

This project aims to bridge the understanding of singers' subjective acoustic response with objective acoustic parameters. The results of the study may be used to inform architectural considerations when designing or retrofitting a performance venue to support unamplified vocal ensembles. It may also be of use to directors when considering suitable performance venues.

Those who may be interested in the outcomes of the study would fall into two broad categories: musicians and designers. Musicians would include singers themselves, conductors and directors, and by extension ensemble managers for sourcing venues. Designers would generally include acousticians, architects, and interior designers.

1.3 Relevant Literature

1.3.1 Auditoria and stage acoustics

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 [1] on stage support and Barron [2] on subjective response. Many of these studies and those that followed were inspired by a paper published in 1978 by Marshall et al. [3] on the 'Acoustical conditions preferred for ensemble'.

Dammerud [4] in 2009 and more recently Panton [5] in 2017 have completed doctorate research programmes on the stage acoustics as experienced by classical instrumentalists. Both these focused on orchestral or chamber musicians in concert halls and auditoriums. Panton's investigations included subjective assessments from an Australian Chamber Orchestra tour of eight Australian concert halls [6].

Some other studies which involve surveying musicians on tour have been conducted with the Netherlands Students Orchestra in seven concert halls in the Netherlands [7], and the Japanese Philharmonic Symphony Orchestra in seven European halls [8]. Some other studies have been conducted by surveying musicians on venues in which they perform frequently, such as Sanders' study of New Zealand halls [9]. The main disadvantage of these studies being that the responses rely on the musicians' memories.

Most of these studies with instrumentalists were conducted around purpose-built concert halls which are typically designed for the modern symphony orchestra. However, it is not a given that

---

[2] Australia Tour Diary – New Zealand Youth Choir nzyouthchoir.com/australia-tour-diary/

choirs would perform in venues which are designed to prioritise choral acoustics. It was anticipated that the variation in subjective response to stage acoustics from choral singers would be much greater than the orchestral studies.

1.3.2 Room acoustics for singers, vocal ensembles and choirs

One of the earliest studies on vocal ensembles was undertaken by Marshall & Meyer [10] on 'The directivity and auditory impressions of singers' and published in 1985. In contrast to the conclusions in the 1978 paper by Marshall et al. in support for early reflections [3], it was found that reverberation was of greater importance to the singers compared to instrumentalists. The experiment was conducted in a hemi-anechoic chamber with simulated reverberation times of 0, 1, 1.5 and 3 seconds.

Thirty-five years later, a follow-up study was conducted by van den Braak et al. [11] which further supported the importance of reverberation for vocal ensembles. They also noted that research for preferred conditions for singers and musicians conducted in the time between the studies "all conclude that early reflections on stage are preferred."

Burd & Haslam [12] circulated questionnaires to choirs and found a preference for St David's Hall (Cardiff) over Glasgow Royal Concert Hall in terms of "contact" between choir and orchestra. St David's was found to have greater reverberant energy when measured across the choir seating area.

Fischinger et al. [13] 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*. Other studies have investigated the preferred reverberation time for conductors and listeners, but rarely for singers themselves.

A study of a "touring" choir was published by Bonsi et. al [14], surveying eleven Venetian churches with the St John's College Choir in 2007. This study focused on the audience's subjective responses rather than the performer. The study concluded that there were strong correlations between audience-perceived "reverberance" with the parameters EDT and T_{30}, and "clarity" with C_{80}. The churches had a large range of reverberation times, with EDT values of between 1.5 to 6 seconds as measured in the audience seating area.

Brereton [15] completed doctorate research in 2014 on singers in real and virtual acoustics environments. It included a case study 'Quartet singing in the *Real Performance Space*' of a SATB quartet singing in *The National Centre for Early Music in York*, a space which allows for adjustable room acoustics. The singers sang three pieces by Thomas Tallis in three acoustic configurations of different reverberation times and were asked for their subjective impressions. With the limited sample size, there was no clear agreeance on the preferred room conditions. Nevertheless, all singers commented on the effect of room acoustics on ease of synchronisation, maintaining stable intonation, and the differing levels of support. Brereton also commented on the low levels of "empirical research which investigates vocal performance in different acoustics in particular."

As part of a Masters thesis, Hom [16] conducted a study with a mixed SATB choir of 11 choristers singing Tye's *Laudate nomen domini* in a Rehearsal Room and a Performance Hall. Hom obtained T_{20} and EDT measures of the two spaces but did not conduct any correlative analysis on the acoustic data. With the spaces unoccupied, the measured T_{20} values at mid-frequencies using a swept since signal was 2.13 seconds in the Rehearsal Room and 1.50 seconds in the Performance Hall. Statistical analysis of the subjective data showed that choristers reported a greater ability to hear themselves within the Performance Hall, and no statistical difference on the reported ability to hear others between the two spaces. Most choristers perceived that the choir performed the best in the Performance Hall, but most listeners preferred the Rehearsal Room recording.

Tonkinson [17] investigated the tendency for choristers to sing with greater vocal intensity to increase feedback over masking of other voices, also known as the "Lombard" effect. The study showed that most singers succumbed to the effect, but were able to resist when instructed to.

Ternström [18] proposed a self-to-other ratio (SOR) metric, which measures a singer's "self" signal of airborne and bone-conducted sound compared with the direct and reverberant feedback of "others'" voices. This metric was found to be highly influenced by singer spacing within the choir, as well as the room acoustics, and a preferred SOR was dependent on the individual [19]. The study showed preference of this ratio ranged from –1 to 15 dB with an average of 6.1 dB, indicating a preference for one's own voice to be heard 6.1 dB louder than the rest of the choir. In general, sopranos and tenors in the study preferred higher SOR to altos and basses.

Since 2018, Luizard et al. have published a range of studies with solo singers' adaptation to room acoustics which involve monitoring their vocal behaviour. These studies have shown some general trends on vocal adaptation to room acoustics. However, evidence shows that patterns in adaptation are largely variable between individuals [20].

A recent study published in 2023 was conducted by Redman et al. [21] on solo singers' perceptions of room acoustics. The room measurements were conducted with a head and torso simulator (HATS) which accounted for inter-aural response and allowed for measurements of the metric ST_V (voice support). The paper presented three semantic factors of Room Supportiveness, Room Noiselessness, and Room Timbre that were shown to account for all subjective characterisations of the acoustic environment by the singers. ST_V was found to have a significant negative relationship with Room Supportiveness, indicating a preference for greater sound energy in the direct mouth-to-ear sound compared to the reflected sound field.

Figure 2: NZYC performing *The City and the Sea*[3] at Ian Roach Hall, Scotch College (© Lucas Packett Photography 2022)

---

[3] *The City and the Sea* by Eric Whitacre performed by the NZ Youth Choir youtu.be/gOGqTCMl5_o?si=foKdp2ZDT0luITlu

2.0 SUBJECT BACKGROUND

2.1 Choir Background

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 degree 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 to name a few.

Members of NZYC generally have a basic level of understanding of responding to acoustic environments, typically through their personal experiences as a musician. It is generally accepted that choral singers adjust their singing technique based on the acoustic environment [22], [23]. The NZYC music staff may also ask for modified techniques to enable a desired sound as heard by the audience.

Modified formations are also considered in the interest of improving both singer response and audience experience [24]. The music director comments that a "more resonant space" will influence the allocation of singer spacing, and the slower tempo at which the pieces are conducted.

Figure 3: NZYC performing *Ko ngā waka ēnei* at Ian Roach Hall, Scotch College (© Lucas Packett Photography 2022)

2.2 Venue Details

The tour began in Auckland 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 for is presented in Table 1.

The list is not exhaustive of all venues that NZYC performed in, and only includes venues at which a concert programme was performed. Some performances were of an informal or ad hoc basis, or were in environments not suitable for acoustic measurements (e.g., outdoors), or the tour schedule did not allow enough time for measurements.

Refer to Appendix F for photos and architecture drawings of each venue.

Table 1: List of performance venues

Performance Venue	City	Performance Date	Room Volume
St Matthew-in-the-City	Auckland	26 November 2022	11200 m^3
The Farrall Centre, The Friends' School	Hobart	28 November 2022	4350 m^3
St David's Cathedral	Hobart	29 November 2022	6750 m^3
Ross Uniting Church	Ross	1 December 2022	790 m^3
Holy Trinity Anglican Church	Launceston	1 December 2022	5400 m^3
St Paul's Cathedral	Melbourne	3 December 2022	23300 m^3
Ian Roach Hall, Scotch College	Melbourne	4 December 2022	–
Dorothy Pizzey Centre, St Catherine's School	Melbourne	5 December 2022	4850 m^3
Christ Church St Laurence	Sydney	14 December 2022	4600 m^3
Sydney Opera House, Concert Hall	Sydney	14 December 2022	24500 m^3

The room volume of each performance space has been estimated and rounded to the nearest 50 m^3 (except for Ross Uniting Church which is rounded to the nearest 5 m^3) based on the architectural plans attached in Appendix F. Drawings could not be obtained for Ian Roach Hall. The Sydney Opera House Concert Hall volume was taken from original acoustician Jordan's book [25].

The room volume of St David's Cathedral does not include the volume of the chancel, as there was a glazed partition separating the nave and transept from the chancel. The volume of the chancel has been included for all other neo-Gothic churches.

Acoustic measurements were not undertaken in Ian Roach Hall and Sydney Opera House. NZYC were guest performers at the concerts in these two venues, and time could not be separately allocated for measurements. However, questionnaires were still collected as both spaces have been designed with significant input from acousticians within the last two decades [26], [27].

3.0 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. This was conducted on an "opt-in" basis, with aims to get at least two respondents from each of the eight voice sections.

The questionnaire was formulated with influence from similar studies conducted by Panton et. al [28] and Sanders [9]. 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 [29] 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.

In the interest of increasing response rate by making the questionnaire more accessible on the go, the questionnaire was directly transferred to a Google Form. This allowed singers to respond using their personal electronic devices. This also allowed for regular reminders to be sent out to an online group chat after each concert with a direct link to the Google Form.

Both forms of the questionnaire and instructions are attached in Appendix D.

The NZYC performs in formations that are designed to optimise the effect of each piece for the audience, and these sometimes change from venue to venue. For this reason, data regarding the singers' positions or choir formation have not been gathered. It is assumed that the average singer would have sung at multiple positions across the stage and would have a general impression of how the acoustic properties vary across the stage. This contrasts with orchestras, which would generally have fixed positions within their instrument sections and relative to the whole orchestra.

3.2 Measurement Parameters

3.2.1 Stage support conditions

The generally accepted acoustic stage condition parameters for orchestras are ST_{Early} and ST_{Late}, proposed and revised by Gade [29] and included in ISO 3382-1 since 1997. These parameters are summarised in ISO 3382-1:2009 Table C.1 and reproduced in Table 2 below.

Table 2: ISO 3382-1:2009 Table C.1 – *Acoustic parameters measured on orchestra platforms*

Subjective listener aspect	Acoustic quantity	Single number frequency averaging	JND (just noticeable difference)	Typical range
Ensemble conditions	Early support, ST_{Early}, in decibels	250 to 2000 Hz	Not known	–24 dB; –8 dB
Perceived reverberance	Late support, ST_{Late}, in decibels	250 to 2000 Hz	Not known	–24 dB; –10 dB

It is worth noting that these stage support parameters have been designed based on experiments conducted with orchestral musicians, and not singers. A pilot study by Miranda Jofre et. al of singer stage acoustics have used the voice support metric ST_V [30], which also accounts for bone and body conduction from the mouth to the cochlea. However, it is understood that this metric was proposed by Pelegrín-García [31] in relation to work by Brunskog et al. [32] on speech rather than singing.

Some studies on singers have included measurement of the interaural cross correlation (IACC), which measured the difference in auditory feedback between the two ears of a person. However, this and

ST_V is measured using a head and torso simulator (HATS) which is not suitable to transport on an international tour.

ST_{Early}

The early support parameter ST_{Early} (originally ST1) indicates the level difference between direct (including floor reflection) sound and reflected sound arriving within the 20–100 millisecond time range. This parameter is intended to be related to hearing one's own instrument, and ease of hearing other members in the orchestra [33]. The equation is as follows:

$$ST_{Early} = 10 \log \left[\frac{\int_{0.02}^{0.10} p^2(t)dt}{\int_{0}^{0.01} p^2(t)dt} \right] \text{dB}$$

The Early Ensemble Level (EEL) was developed with the intention to indicate the ability to hear others on stage. However, studies have shown stronger correlations for ST_{Early} to 'hearing of others,' and so this metric is not as widely used [1].

ST_{Late}

The late support parameter ST_{Late} indicates the level difference between direct (including floor reflection) sound and reflected sound arriving within the 100–1000 ms time range. This parameter is intended to be related to the room response or reverberance of the hall as heard on stage [33]. The equation is as follows:

$$ST_{Late} = 10 \log \left[\frac{\int_{0.10}^{1.00} p^2(t)dt}{\int_{0}^{0.01} p^2(t)dt} \right] \text{dB}$$

Clarity factors

The Clarity factor C_{80} describes the proportion of early to late reverberant energy, and also known as the 'clarity factor' when measured on stage. When measured at a source-receiver distance of 1 metre, it is intended to indicate the "reverberation level," but this metric was found to be better represented by ST_{Late} [1]. Nevertheless, the C_{80} may provide additional detail in spaces with long reverberation times due to accounting for total late reflections (rather than late reflections up to 1000 milliseconds as in ST_{Late}). The equation is as follows:

$$C_{80} = 10 \log \left[\frac{\int_{0}^{0.08} p^2(t)dt}{\int_{0.08}^{\infty} p^2(t)dt} \right] \text{dB}$$

An alternative clarity factor C_{50} is commonly used for speech clarity, whereas C_{80} is generally used for music clarity. C_{50} is defined analogously to C_{80} in regard to integration time limits, and may be more relevant to this study due to the presence of consonants in both speech and vocal music.

3.2.2 General auditorium measures

Reverberation Time

Reverberation time (RT or T_{60}) describes the time it takes for interrupted sound to decay within a space and is one of the most common metrics used in room acoustics. The reverberation time RT is based on a 60-decibel decay, as defined by Sabine in 1898. However, in practice the time for a 60-decibel decay is extrapolated from a 30-decibel decay. A 20-decibel decay is used if there are elevated background noise levels.

Bass Ratio

Bass Ratio (BR) is quantified as the ratio between the sum of the RTs in the 125 and 250 Hz octave-bands divided by the sum of the RTs in the 500 and 1000 bands. This metric quantifies the amount of low-frequency reverberant energy compared with the mid frequencies, with the high BR relating to richness and warmth of the lower frequency sounds. The metric was proposed by Beranek [34] in 1962, and his further work indicated its subjective importance in concert hall acoustics [35]. The equation is as follows:

$$BR = \frac{RT_{125Hz} + RT_{250Hz}}{RT_{500Hz} + RT_{1000Hz}}$$

The basses in a typical mixed choir would have notes with fundamental frequencies of up to 260 Hz. In the tour repertoire, the lowest note for the Bass 2s was C2, corresponding to approximate fundamental of 65 Hz, with many other notes below 150 Hz.

Treble Ratio

Beranek also discussed the concept of "liveliness" relating to the ratio of reverberation time of frequencies 2000 Hz and above with the mid-frequencies. Treble Ratio (TR) is quantified as the ratio between the sum of the RTs in the 2000 and 4000 Hz octave-bands divided by the sum of the RTs in the 500 and 1000 bands. The equation is as follows:

$$TR = \frac{RT_{2000Hz} + RT_{4000Hz}}{RT_{500Hz} + RT_{1000Hz}}$$

The highest note sung in all tour repertoire by a small group of Soprano 1s was D6, at an approximate fundamental of 1175 Hz, with most notes below 1000 Hz. The TR would only be indicative of the subjective effects relating to the overtones in the voice. Bonsi et. al for their audience-based study found positive correlations between TR and "clarity" and "brilliance" in addition to "reverberance" in their study in large Venetian churches [14]. Larger churches were found to have lower TR, due to the increase in molecular air absorption of sound energy. There are limited studies that show the influence of TR on stage acoustics.

ISO-3382-1 listener aspects

ISO-3382-1 also proposes a range of acoustic quantities that are related to listeners which are generally in the audience. The relevant rows are reproduced in Table 3.

Table 3: ISO-3382-1 Table A.1 – ***Acoustic quantities grouped according to listener aspects***

Subjective listener aspect	Acoustic quantity	Single number frequency averaging [a]	JND (just noticeable difference)	Typical range [b]
Subjective level of sound	Sound strength, *G*, in decibels	500 to 1000 Hz	1 dB	–2 dB; +10 dB
Perceived reverberance	Early decay time (EDT) in seconds	500 to 1000 Hz	Rel. 5%	1.0 s; 3.0 s
Perceived clarity of sound	Clarity, C_{80}, in decibels	500 to 1000 Hz	1 dB	–5 dB; +5 dB
Apparent source width (ASW)	Early lateral energy fraction, J_{LF} or J_{LFC}	125 to 1000 Hz	0.05	0.05; 0.35
Listener envelopment (LEV)	Late lateral sound level, L_J, in decibels	125 to 1000 Hz	Not known	–14 dB; +1 dB

[a] The single number frequency averaging denotes the arithmetical average for the active bands, except for L_J which shall be energy averaged.

[b] Frequency-averaged values in single positions in non-occupied concert and multi-purpose halls up to 25000 m^3.

Annex A.5 of the standard states that "The measurement results for the measures described in this annex should normally not be averaged over all microphone positions in a hall because the measures are assumed to describe local acoustical conditions." However, these metrics are typically measured in the audience area over a large area compared to the stage area. It's assumed that the listener aspect metrics may be averaged when measured on stage.

Sound strength

The Sound strength or Loudness factor G is usually used to quantify the sound strength as received in the audience. The equation is as follows:

$$G = 10\log\left[\frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_{10m}^2(t)dt}\right] \text{dB}$$

The integration times may be modified to measure sound strength before and after 80 milliseconds, to obtain the metrics G_{Early} and G_{Late}. The equations are as follows:

$$G_{Early} = 10\log\left[\frac{\int_0^{0.08} p^2(t)dt}{\int_0^\infty p_{10m}^2(t)dt}\right] \text{dB} \qquad G_{Late} = 10\log\left[\frac{\int_{0.08}^\infty p^2(t)dt}{\int_0^\infty p_{10m}^2(t)dt}\right] \text{dB}$$

Some studies have used G_{Late} to quantify the strength of reverberant energy that is reflected back to the stage, notably after 80 milliseconds of the initial sound. Studies have presented this as an alternative to ST_{Late}, and relevant to support and projection [4].

Early Decay Time

Early Decay Time (EDT) measures the slope of reverberation decay for the first 10 decibels, extrapolated out to 60 decibels. This metric is only useful for stage measurements taken with a source-receiver distance of much greater than 1 metre, particularly in rooms with low reverberation times, as the measurements are highly influenced by early reflections. The EDT is the same as the RT for pure exponential decay in a diffuse field.

Lateral fraction

Marshall & Meyer [10] recommend that stage design should include side rather than overhead reflectors, due to the measured directivity of ensemble singers' voices. The argument for lateral reflections is somewhat supported by a more recent study with five solo singers, which showed preference for side reflections over rear reflections [36].

The early lateral energy fraction J_{LF} for a listener in the audience corresponds to apparent source width, and the late lateral sound level L_J corresponds to listen envelopment. The equation is as follows:

$$J_{LF} = \frac{\int_{0.005}^{0.08} p_L^2(t)dt}{\int_0^{0.08} p^2(t)dt}$$

However, these metrics are generally excluded among discussion on design for stage acoustics and there are limited studies that quantify its effect.

3.3 Measurement Methodology

To gather acoustic data from each of the venues, the frequency response was measured at various source and receiver locations across the "stage." In this context, not all venues had what would traditionally be called a stage (i.e., a raised performance platform), and this is defined as the area in 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* [37], using a swept-sine signal in accordance with ISO 18233:2006.

The hardware used was the "IRIS Mini" kit (Figure 4) developed and tested by Marshall Day Acoustics [38]. This system uses consumer-grade equipment and wireless receivers, and has significant portability benefits over traditional methods which use a large dodecahedral speaker sound source. These were important factors to consider due to the logistics of international touring. The Bose Soundlink Revolve+ II Bluetooth speaker source has been shown to generally conform within omnidirectionality tolerances as prescribed in ISO 3382-1:2009, particularly along the circumferential plane. The main disadvantage of using the system was that it occasionally could not generate sufficient sound energy at the low frequencies to allow for good signal-to-noise ratio.

Figure 4: IRIS Mini kit Bose Soundlink Revolve+ II speaker source (left) and Zoom H3-VR receiver (right)

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

This IRIS Mini kit has a number of limitations. It's understood that measurements with the Zoom H3-VR microphone used with the IRIS Mini kit has not been fully validated for the lateral energy parameters. Furthermore, the strength (G) calibration file has been created using another kit with a different set of wireless transmitters. For the purposes of this study, comparisons of the lateral fraction and strength parameters will be qualitative only.

3.4 Measurement Locations

The measurement locations were selected to gather a moderate spread of data across the stage, keeping in mind the limited testing time (Figure 5). In general, the testing was completed within half an hour. Each position as described is relative to the dimensions of each venue stage, rather than absolute positions.

The testing was generally divided into four "sets" of source locations, and the acoustic response was measured at each of these. Sets A, B and C included measurements with the receiver a 1 metre in front of and to the side of the source, to determine the stage support parameter. Sets A and B also included one other location across the stage with the aims of understanding cross-stage aspects.

Set A was conducted with the source in the Downstage right position, representative of the right-most singer within the choir on the stage. The cross-stage receiver location was Downstage left, for which the source-receiver distance would be considered representative of the greatest distance between two singers. These positions were ensured to be at least 2 metres away from the nearest vertical surfaces as recommended in ISO 3382-1:2009 Annex C.

Set B was conducted with the source in the Mid-stage left position, approximately one-third of the stage width towards the centre from the edge. The cross-stage receiver location was Mid-stage right, at a similar distance in from the edge. This would be considered representative of the average singer-to-singer distance within the choir.

Set C was conducted with the source in the Upstage centre position, and in some venues was on a riser. This location would be considered representative of the singer that is the furthest from the audience.

Set D was conducted with the source in the Centre stage position, with the receiver at the conductor's position. This would be considered representative of the average distance between a chorister and the conductor.

A Insta360 One X 360-degree camera was used to take a photo of each of the space from the conductor's position.

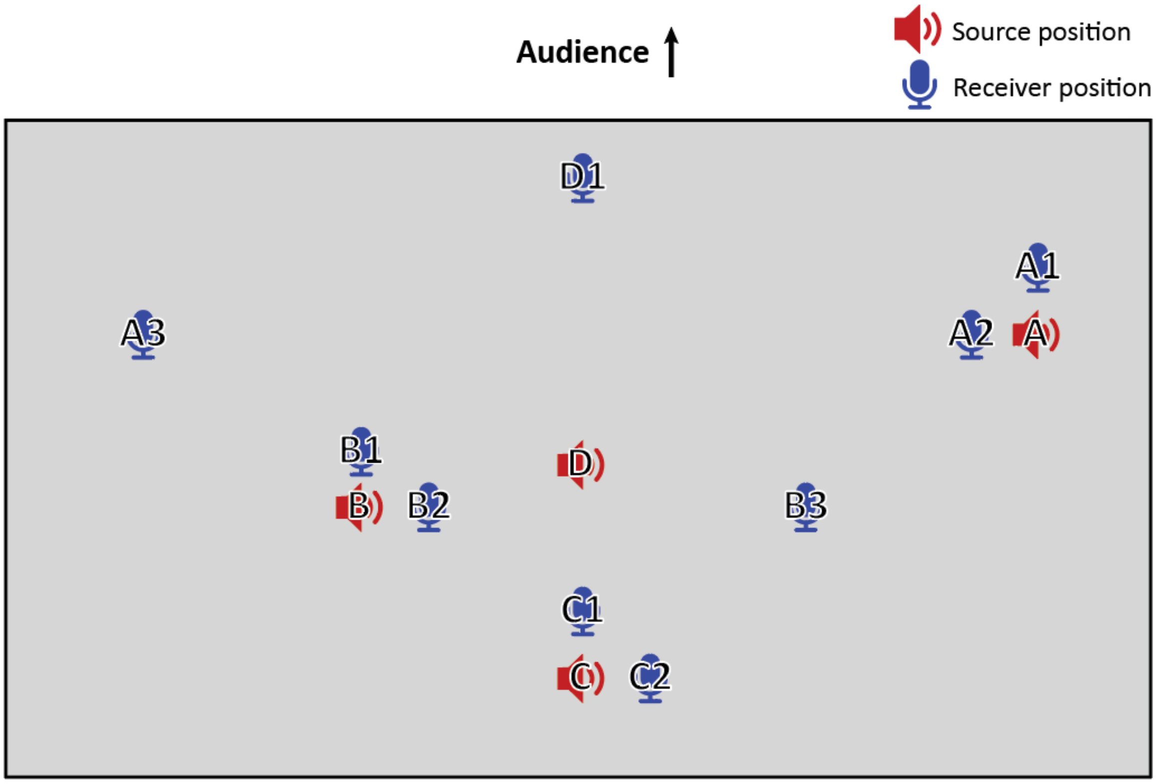


Figure 5: Generic schematic of source and receiver locations of acoustic measurements

Not all sets of locations were measured if the stage was either too small, or if it presented physical challenges (i.e., balustrades or riser height discrepancy).

4.0 RESULTS

4.1 Questionnaire Response Metrics

4.1.1 Response rate

A total of thirty (30) singers participated in the questionnaire which accounted for between 33% to 100% of each voice part section. A summary of response rate is presented in Table 4.

Table 4: Summary of respondent participation across the voice part sections

Voice Part	Respondents	Percentage of Section	Voice Part	Respondents	Percentage of Section
Soprano 1	3	50%	Tenor 1	4	80%
Soprano 2	4	67%	Tenor 2	4	80%
Alto 1	3	50%	Bass 1	2	33%
Alto 2	5	100%	Bass 2	5	100%

Five (5) of the respondents opted to use the paper or PDF versions of the survey, and twenty-five (25) used the online Google Form. No conclusions or speculations have been made on whether or not there was any influence of the format on the questionnaire responses. For the purposes of this study, responses from both formats have been treated as equivalent.

The response rate across the venues ranged from 47% to 83% of the total number of respondents. A summary of the response rate is presented in Table 5. A total of 209 unique responses was collected from the singers. Some singers were absent from various concerts due to infection with Covid-19, hence not all respondents were present at all venues.

Table 5: Summary of questionnaire response rate between venues

Venue	Acronym	Respondents	Percentage of Total Respondents
St Matthew-in-the-City	SMC	25	83%
The Farrall Centre	TFC	25	83%
St David's Cathedral	SDC	24	80%
Ross Uniting Church	RUC	23	77%
Holy Trinity Anglican Church	HTA	20	67%
St Paul's Cathedral	SPC	20	67%
Ian Roach Hall	IRH	14	47%
Dorothy Pizzey Centre	DPC	17	57%
Christ Church St Laurence	CSL	22	73%
Sydney Opera House, Concert Hall	SOH	20	67%

The data was analysed using the RStudio (2023.12.1 Build 402) integrated development environment (IDE), which uses the programming language R for statistical computing and graphics.

4.1.2 Median and interquartile range

Semantic differential scales, similar to Likert scales, are generally accepted as ordinal. The scale implies a rank order but is not assumed to have an even distribution between categories or intervals. However, the questionnaire presented was an 11-point scale, and contained an arbitrary zero point at “5”. It can be argued that the scale value may be treated as an interval scale due to the larger number of intervals when compared to a typical 5- or 7-point scale, with equal distance between them. This is assumed for the statistical methods applied.

A list of the subjective metrics and abbreviations is summarised in Table 6. The full singer questionnaire is included in Appendix D.

Table 6: List of subjective metrics and abbreviations

Subjective metric	Abbreviation	Subjective metric	Abbreviation	Subjective metric	Abbreviation
Overall Acoustic Impression	OAI	Ensemble	Ens	Timbre	Tim
Hearing Self	HeS	Reverberance	Rev	Dynamic Range	DyR
Support	Sup	Clarity	Cla	Visual Impression	Vis

Medians and interquartile ranges are appropriate for data which may not be normally distributed. The subjective data has been analysed, and the medians and interquartile ranges are summarised in Table 7. Refer to the sub-sections under Section 4.2 for histograms and boxplots for individual venues.

Table 7: Median singer response and interquartile ranges for subjective characteristics for each venue

		SMC	TFC	SDC	RUC	HTA	SPC	IRH	DPC	CSL	SOH
Median (Interquartile Range)	OAI	8 (7–9)	6 (5–7)	7 (6–8)	7 (6–7.5)	8 (6–8)	8 (7–8.25)	9 (8–9.75)	5 (4–6)	8 (7.25–9)	9 (8.75–10)
	HeS	8 (7–9)	7 (3–9)	8 (5.75–8)	7 (4–8)	8 (6–8)	7 (6.25–8.25)	8 (7–9)	7 (6–8)	8 (7–8)	8.5 (8–10)
	Sup	7 (4–8)	4 (2–6)	7 (4.75–7)	7 (5.5–8)	6.5 (5–7.25)	7 (6–8)	8 (7.25–8.75)	6 (5–7)	8 (7–9)	8 (7–10)
	Ens	7 (5–8)	5 (3–7)	6 (4–7)	6 (4–7.5)	6 (5–6.25)	7 (5.5–8)	8 (7.25–9.75)	6 (6–7)	7 (6–8)	7 (7–9)
	Rev	7 (7–8)	4 (3–5)	7 (5.75–7)	7 (4.5–8)	6 (5–7)	7.5 (6.75–8.25)	6 (5–6.75)	3 (3–4)	7 (6–7)	6.5 (5.75–7)
	Cla	6 (5–7)	7 (6–8)	6 (4–7)	6 (5–7)	6 (5–7)	5.5 (3.75–7)	7.5 (7–9)	7 (5–7)	6 (4–7)	7 (5.75–8.25)
	Tim	5 (3–7)	5 (3–5)	6 (4–7)	4 (3–7)	6 (5–7)	5 (4–6.25)	4 (2.25–5)	5 (4–6)	6 (5.25–7)	3 (2.75–5)
	DyR	8 (7–10)	5 (3–8)	6 (4–8)	6 (5–7)	7 (5.75–7.25)	7 (6–8.25)	7 (7–8)	4 (4–7)	7 (6–8)	7.5 (6.75–10)
	Vis	9 (9–10)	8 (7–8)	9 (8–10)	7 (6.5–8)	8 (6.75–9)	10 (9–10)	9 (8–10)	5 (3–5)	8 (8–9.75)	10 (9–10)

The cells have been shaded to show the venue(s) with the highest median rating in red and the lowest median rating in blue within each subjective metric.

Notably, OAI and Vis had high levels of agreeance, with interquartile ranges for all venues of 2.25 points or less. There were generally very high scores for HeS, Sup and Ens, indicating that all venues or stages were considered at least somewhat suitable for the choral music by the singers. Responses for TFC an RUC generally had larger interquartile ranges compared to other venues.

There is a larger spread of median ratings for Tim. It was hypothesised that the audibility or balance of the different voice parts or a modification in singing technique would correlate with opinions on timbre. However, it is possible that this metric was not as well understood by the respondents or was not the best descriptor for the concepts under investigation. Furthermore, it is also likely that the bone-conduction path significantly affects the timbre of the singers' own voices and may not be indicative of a judgement purely on the response of the room.

4.2 Singer Responses by Venue

4.2.1 St Matthew-in-the-City (SMC)

SMC is located in Auckland, which is approximately where half of the singers were residing for work or study at the time of touring. Many of the singers have performed in this space over the years and are familiar with its acoustic properties for vocal music. This building is a Gothic Revical historic church of Oamaru stone construction.

A leaving concert was held at SMC on 26 November and was a 1-hour programme without interval. The histogram and boxplots of subjective data from the singer questionnaires is shown in Figure 6.

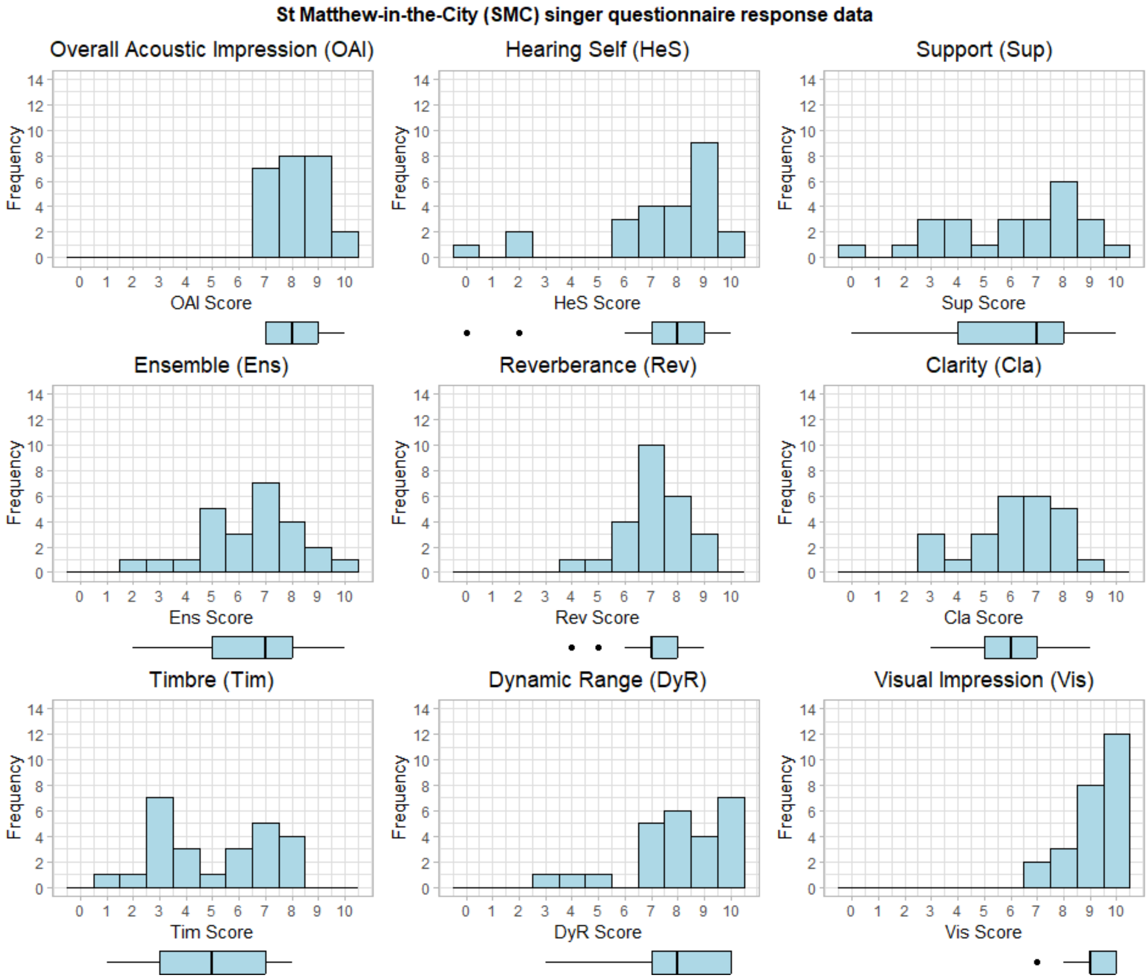


Figure 6: Histogram and boxplots of SMC singer questionnaire responses

Overall, the singers enjoyed singing in SMC, with high points for both OAI and Vis. Three respondents score the venue much lower than the group for Hearing Self, these were two Sop 2s and one Alto 2. There was very little agreeance on Sup, with responses covering the full range of the point scale. There is a noticeable split within the responses for Tim, with one group centred around 3 points and the other group centred around 7 points. The venue had the highest median rating for DyR.

On the hearing of other parts, there were a few comments that the altos were harder to hear, and an Alto 2 noted that the director would gesture for the section to be louder on a number of occasions. A smaller number of comments that the basses were harder to hear. On the contrary, there was similar number of comments that sopranos and basses could be heard very well.

Three respondents noted that there were echoes or reverberant effects from behind the choir. This was likely in reference to acoustic effects from the chancel, which presents as a coupled space with the main nave area.

A small number of singers commented that they used stronger consonants. Some singers felt the need to sing a bit softer to “blend” with others, or so they could hear those around them better.

4.2.2 The Farrall Centre (TFC)

After a day of international travel, the first concert was at TFC on 28 November. This was a short programme of less than 40 minutes and was to the primary school-aged children at The Friend’s School in Hobart. This venue is a multi-purpose school auditorium, constructed in 2010 and seats up to 800 people. The histogram and boxplots of subjective data from the singer questionnaires is shown in Figure 7.

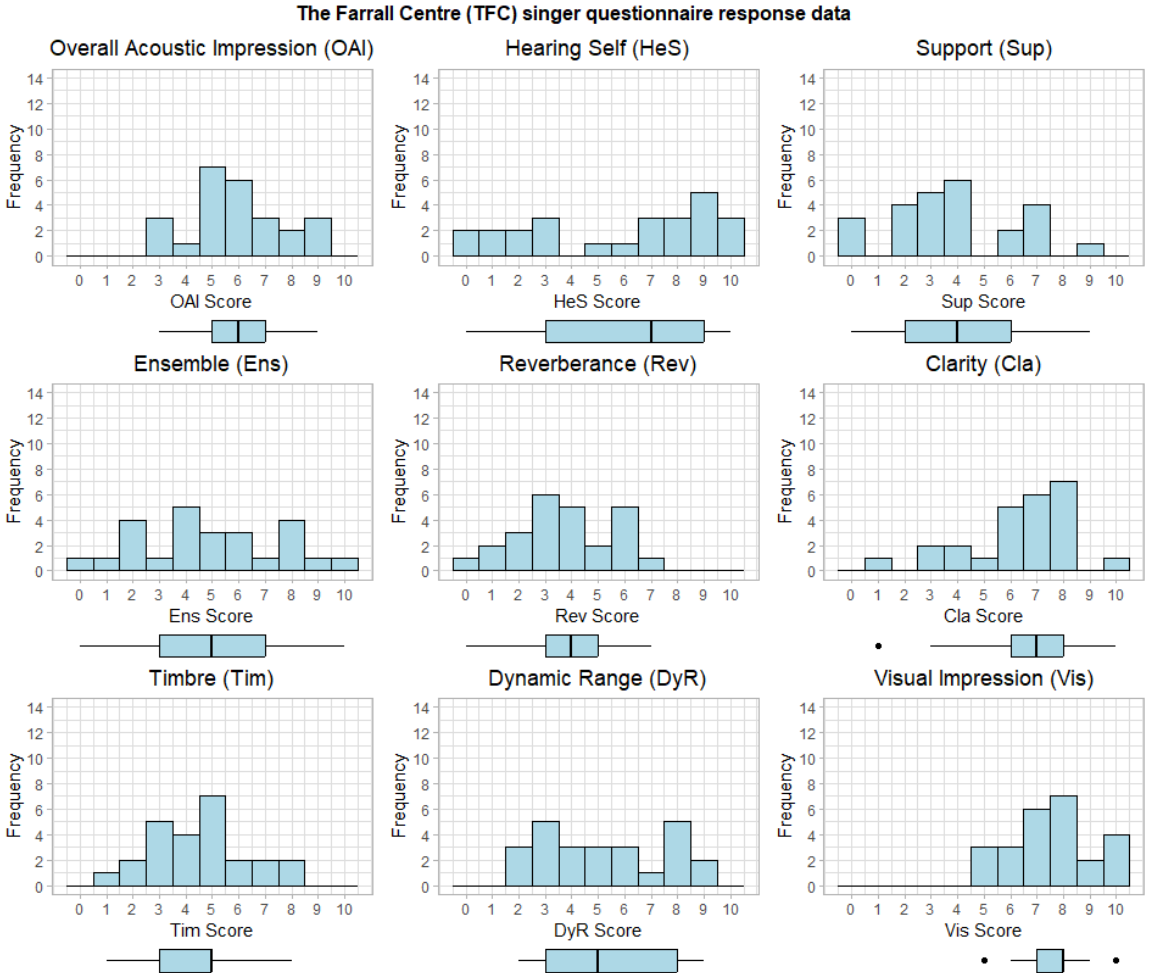


Figure 7: Histogram and boxplots of TFC singer questionnaire responses

Compared to the other venues, responses for TFC appear to have less agreeance, particularly for HeS and DyR. Responses for HeS and Tim covered the full point scale, and Sup covered 10 points out of the 11-point scale. The venue had the lowest median ratings for HeS, Sup and Ens. Overall, the respondents thought the venue was acceptable, but required more work to achieve the desired sound.

There was no general consensus on whether there was a particular voice part that was harder to hear, with some comments that all singers were harder to hear. There were a small number of respondents that could hear the sopranos well, but others who mentioned that not even the sopranos stood out in the space, and that was unusual.

A small number of respondents mentioned that they felt they were starting to push their voice or sang with more overtones so they could hear themselves better. Some also commented that they could hear those in their immediate vicinity but not across the stage.

An Alto 1 noted a "bright reflection" from the side of the stage.

After the concert, the venue manager / AV technician mentioned that the drapes to the rear of the auditorium could be retracted to expose concrete walls. Absorptive drapes are commonly used in multi-purpose spaces to enable variable room acoustics to suit different activities. It is likely that retracting the drapes would have noticeably increased the reverberation time, and enabled acoustic conditions that were more suitable for choral music.

4.2.3 St David's Cathedral (SDC)

The choir's first full concert of the tour with an interval was held at SDC on 29 November in Hobart. This building is a Gothic Revival historic church of Oatlands sandstone construction. The histogram and boxplots of subjective data from the singer questionnaires is shown in Figure 8.

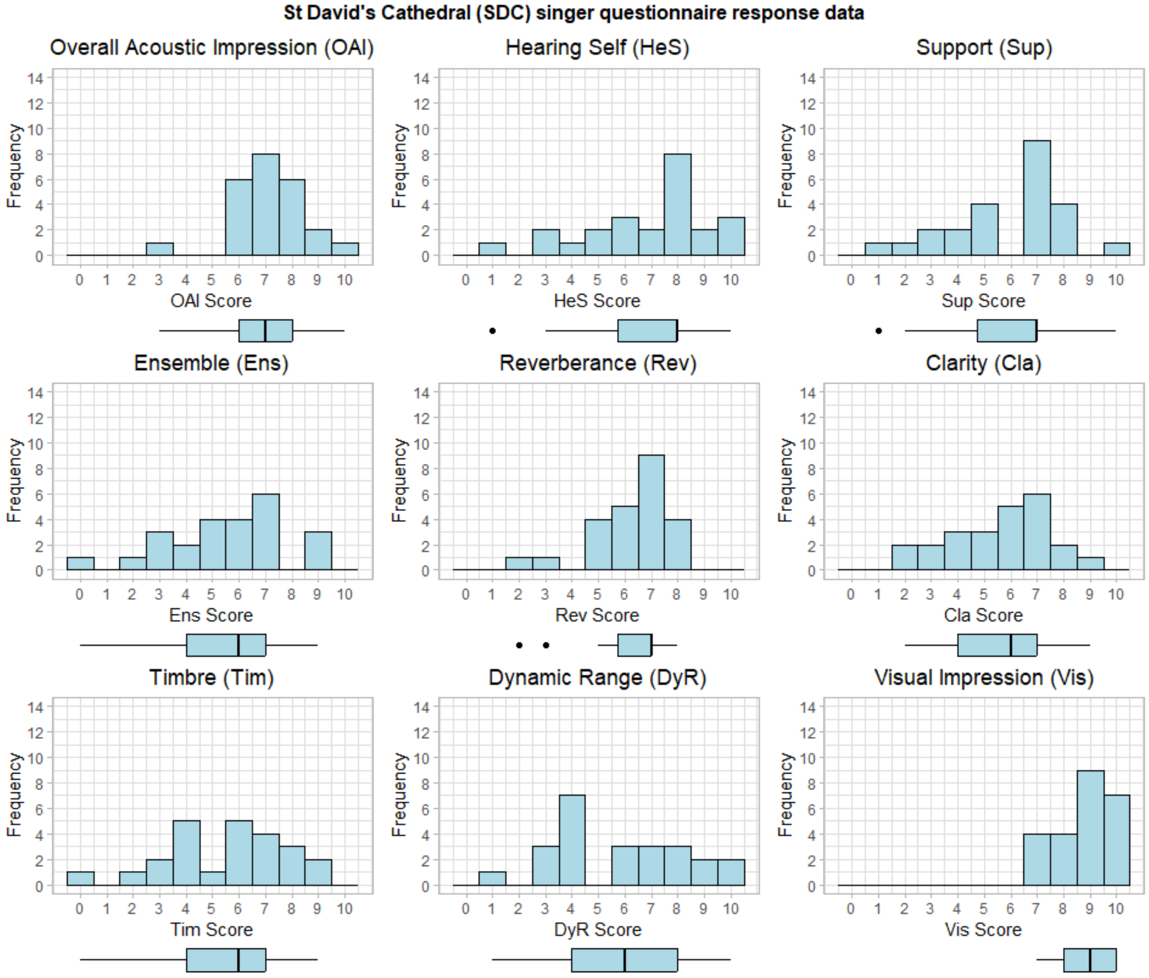


Figure 8: Histogram and boxplots of SDC singer questionnaire responses

The responses for SDC covered a large range of 10 points for HeS, Sup, Ens, Tim and DyR metrics. There was moderate agreeance on Rev. Generally, the spaced worked for most pieces, but posed a challenge for the Waiata-ā-ringa 'Kua Rongo.' The stage wasn't big enough to comfortably accommodate the movement required, and the guitar was difficult to hear across the choir.

More than half of the respondents indicated that the basses were particularly hard to hear, and the sopranos could be heard very well. Some respondents also indicated that the altos were hard to hear and the tenors could be heard well.

A few respondents, the basses and altos in particular, noted they had to sing with a “brighter” tone or with more “cut” so they could have a more present sound in the balance. Notably, these comments were not reflected in the responses for Tim, for which the median puts SDC amongst the venues with the “warmest” or “mellowest” timbre.

One Alto 1 noted that early reflections could be heard, but there was not much reverberance to follow. One Alto 2 noted an echo from the chancel behind the choir.

4.2.4 Ross Uniting Church (RUC)

The choir performed a short programme at RUC on 1 December, during their travel to Launceston. This building is a Gothic Revival historic church of stone construction from the local Beaufront Quarries.

The performance was around midday and was approximately 30 minutes. The histogram and boxplots of subjective data from the singer questionnaires is shown in Figure 9.

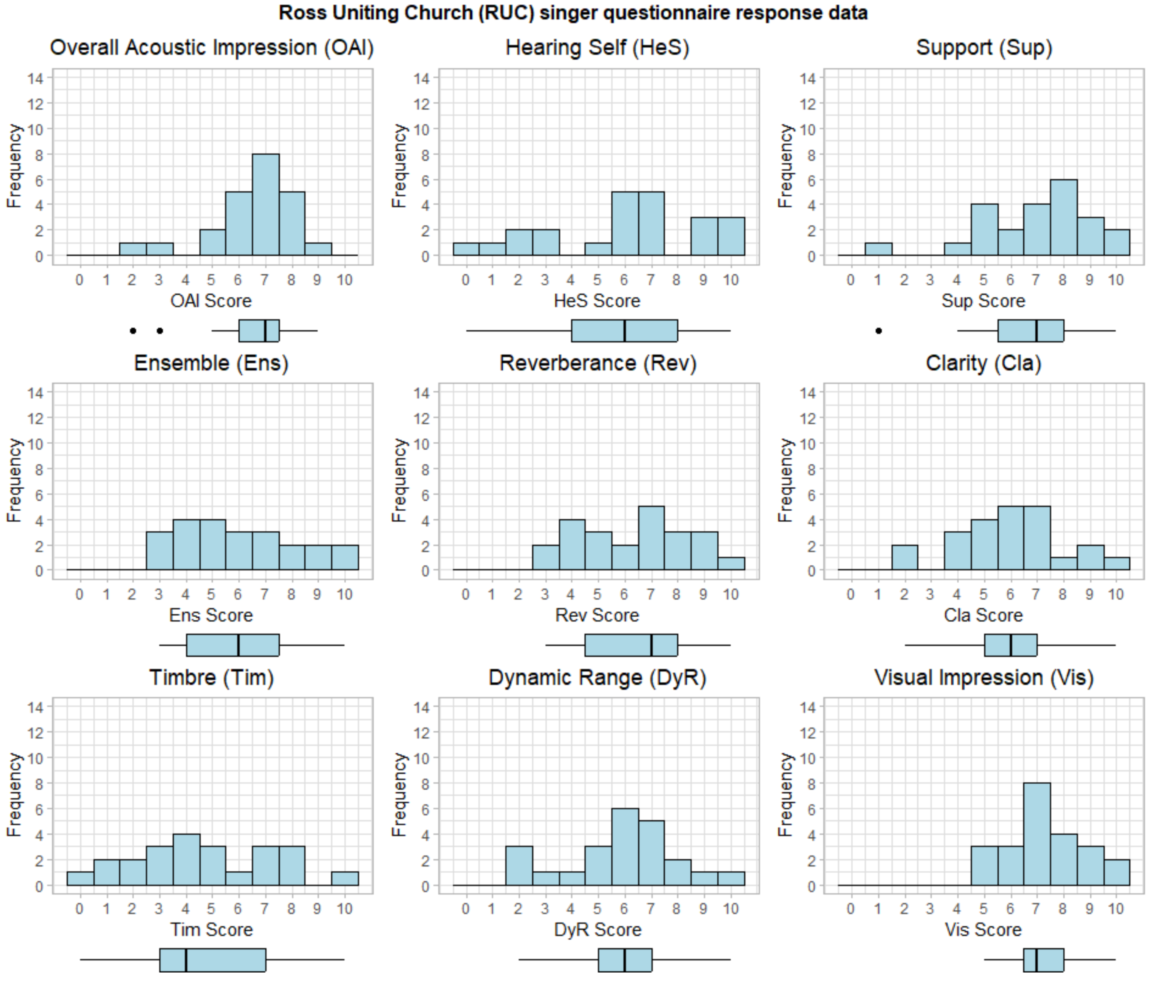


Figure 9: Histogram and boxplots of RUC singer questionnaire responses

The responses for RUC generally had less agreeance across the metrics compared to other church-type venues, in particular HeS and Tim. Due to the smaller room volume and proximity of singers to reflective surfaces, there may have been a larger variation in acoustic properties across the stage, and also between voice parts. A Tenor 2 suggested that the space would suit a smaller ensemble better.

Compared with the other venues, the singers were stood much closer together, and the back row was stood across the pulpit which was significantly higher than stage level. There was no noticeable agreeance on whether a particular voice part could be heard more or less, other than the choir being very loud overall.

Many singers noted that the room was highly responsive to the choir's sound and adjusted to sing softer than typical. However, this meant that many singers had difficulty hearing themselves, and the venue was rated amongst the lowest for HeS. A Tenor 1 noted that he sang with more "shimmer" rather than volume. There were a number of comments that it was difficult to sing the softer dynamics. However, these comments are not particularly well reflected in the responses for DyR, with the median answer indicating that it was marginally easy to achieve variation in dynamics.

The responses for RUC on Rev had the largest interquartile range compared with other venues and were amongst the highest median scores. It is likely that the comparably small room volume influenced the perception of the acoustic properties of the space.

A Tenor 1 noticed an audible beating effect in 'Elijah Rock,' which is arguable the loudest piece in the repertoire and has very high Soprano notes. Many respondents commented on the loud bird noise in/on the roof, which were distracting at times.

4.2.5 Holy Trinity Anglican Church (HTA)

The choir performed a full concert at HTA on the evening of 1 December after arriving in Launceston. This building is a Federation Gothic historic church of red brick and sandstone construction. The histogram and boxplots of subjective data from the singer questionnaires is shown in Figure 10.

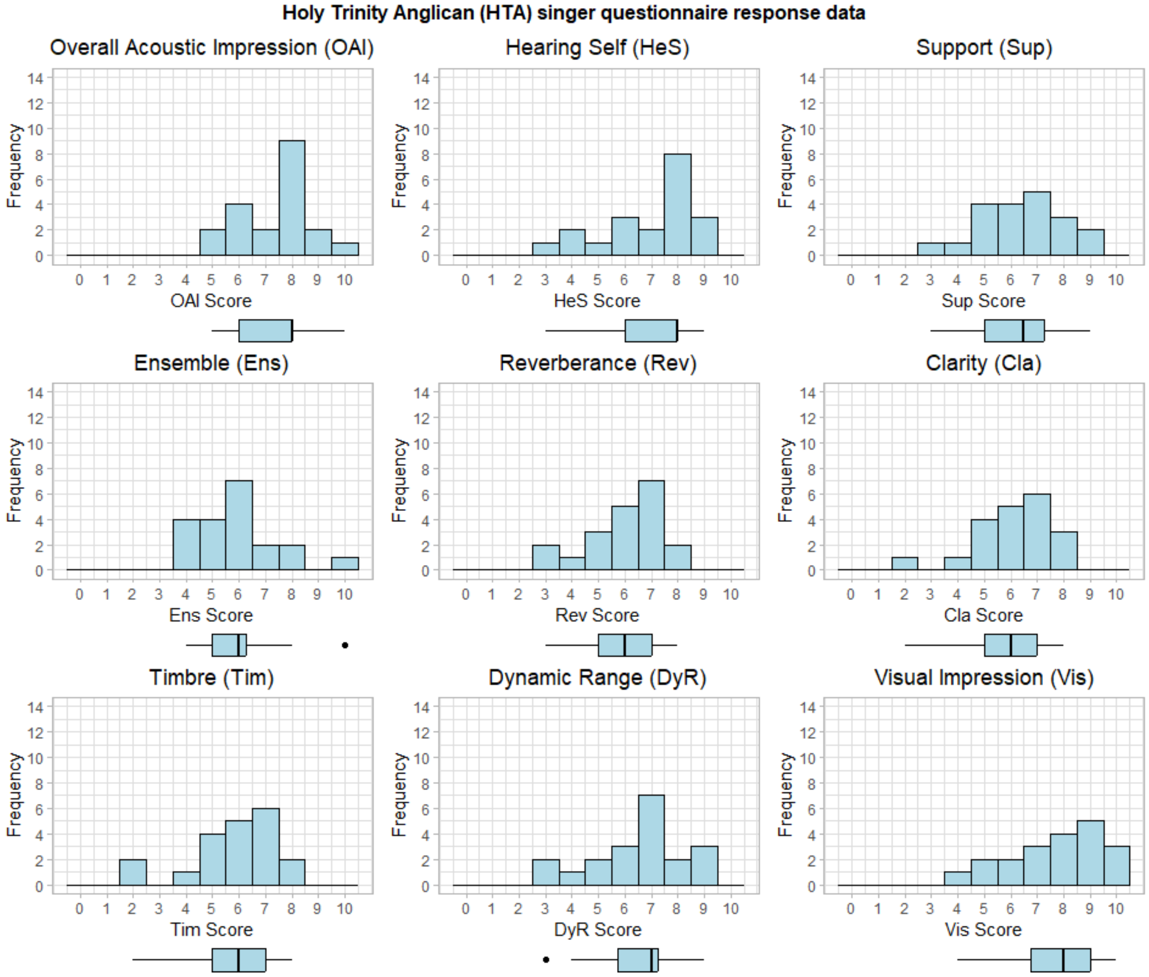


Figure 10: Histogram and boxplots of HTA singer questionnaire responses

HTA was amongst the highest rated for Tim, corresponding to a “warm and mellow” timbre, and was moderately well-liked by the respondents. It was noted that the piano was quite far away and therefore more difficult to hear, which some respondents attributed to getting out of time in the performance of ‘Little Man in a Hurry.’ An Alto 2 also commented that difficulty hearing across the choir may have contributed to getting out of time, and a Tenor 2 also commented on the difficulty of ensemble. The median score for Ens was only marginally below average compared with the other venues.

There were a small number of comments that the sopranos could be heard prominently, and the altos and basses were more difficult to hear. There were also other respondents that felt that it was generally well balanced. A Tenor 1 noted an echo from the chancel behind the choir.

A few respondents commented that it was particularly hard to hear the other choirs in ‘Duo Seraphim.’ This piece is sung with three evenly sized choirs spread around the space.

Two Alto 1s felt that that had to sing with a “brighter” tone or with more “squillo” to ensure their sound was not too warm or heavy, and to help with intonation.

4.2.6 St Paul’s Cathedral (SPC)

The choir performed a full concert at SPC in Melbourne on the evening of 3 December 2022. This building is a Gothic Revival historic church of Barrabool Hills sandstone and Waurn Ponds limestone construction. The histogram and boxplots of subjective data from the singer questionnaires is shown in Figure 11.

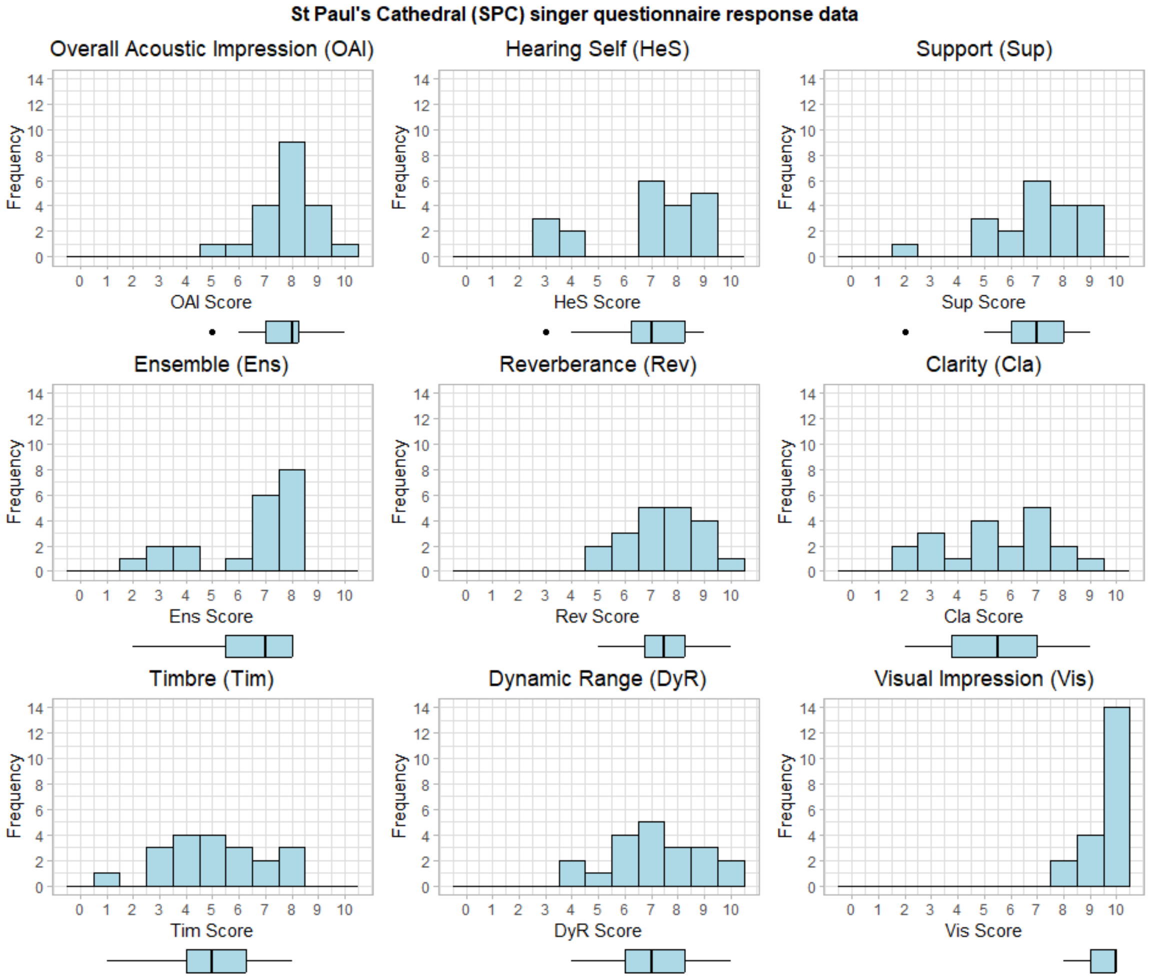


Figure 11: Histogram and boxplots of SPC singer questionnaire responses

Most notably, SPC scored the highest for Vis with 70% of respondents rating it a 10. It also had the highest median score for Rev, with numerous comments on long or “ringy” reverberation and two respondents describing an “echo.” This was the largest space the choir had performed in on the tour at the time, which was only surpassed by SOH. This may have influenced the perception of reverberance. Bonsi et. al also noted probable confusion for non-acousticians of interpreting reverberance and echo as being equivalent acoustic effects [14].

The venue amongst the lowest for HeS. There was no obvious consensus on which voice parts were more difficult to hear, and a small number of comments that the sopranos could be heard more prominently. A Soprano 1 and Bass 2 commented that they made sure to sing with “tall vowels” as instructed by the music staff. A Bass 1 and an Alto 2 commented that they made efforts to increase the clarity of the text with more consonants.

There were a few comments that the faster pieces such as the waiata and ‘Little Man in Hurry’ were difficult to get clear enunciation. Notably, the venue had the lowest rating for Cla amongst the venues. A Soprano 2 also commented that ‘Sunday’ may have been a little “heavy” sounding for the cathedral. The piano accompaniment for the piece contains lots of metric block chords.

4.2.7 Ian Roach Hall (IRH)

The NZYC were a guest choir at Exaudi Youth Choir’s Christmas concert at IRH on 4 December. The choir performed a short set of up to 30 minutes, and participated in two massed items with Exaudi.

This venue is a multi-purpose school auditorium of timber and MDF internal finishes, and seats up to 800 people. The histogram and boxplots of subjective data from the singer questionnaires is shown in Figure 12.

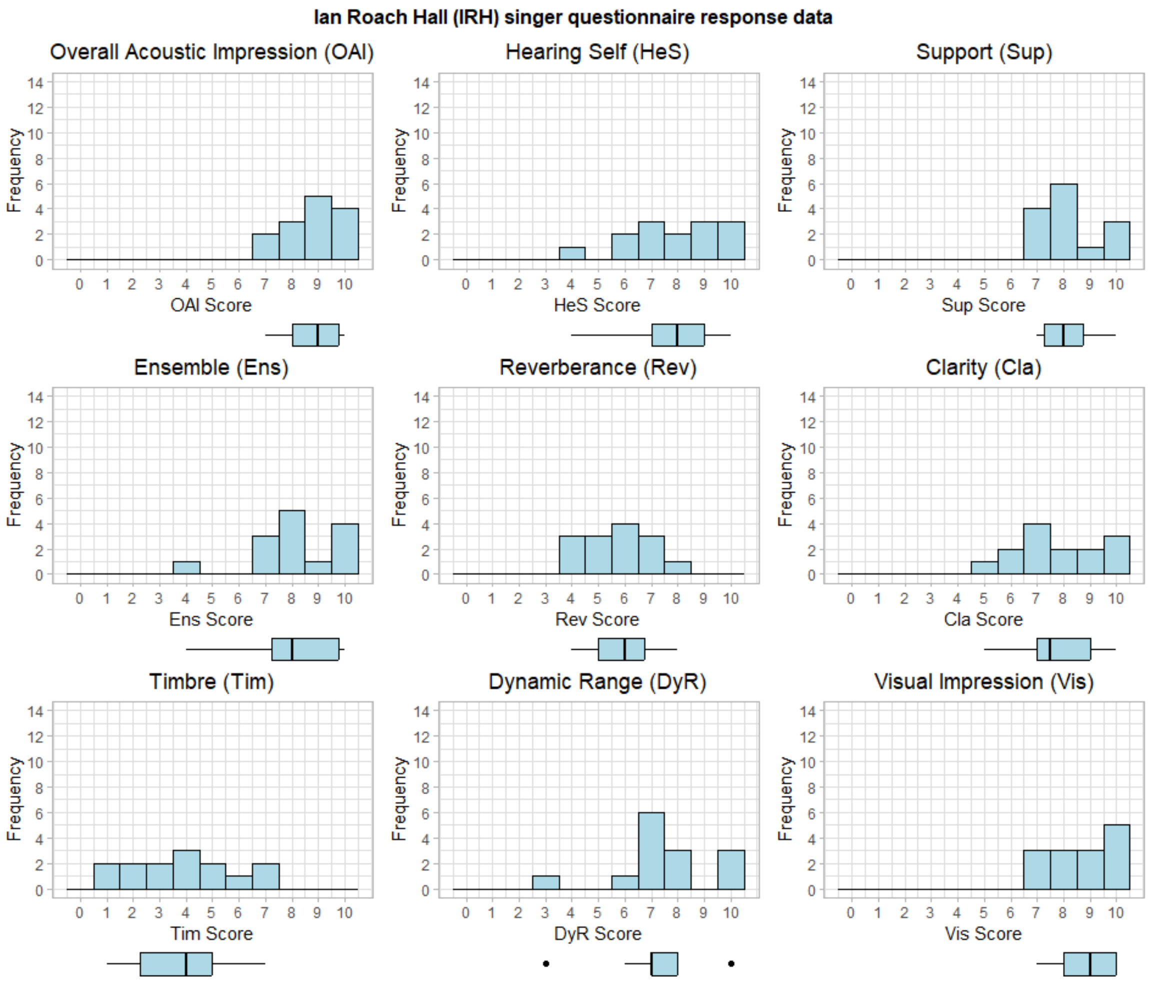


Figure 12: Histogram and boxplots of IRH singer questionnaire responses

This venue had the smallest sample size, due to a number of singers in isolation with Covid-19 infections. The IRH was particularly well-liked, with the highest median ratings for Ens and Cla compared with other venues. It was also rated well for OAI and Sup.

The responses generally indicated that the voice parts were well balanced, with two Sopranos indicating that the Sopranos were heard particularly prominently. This may have been due to an uneven number of singers from each voice part being absent from the performance.

Most respondents felt they could sing normally as the room supported the sound well, even when singing quietly or “thin-fold.” Many commented that the space felt accommodating, with the stage response sounding “rich” and vibrant” but also had clarity. One Alto 1 indicated that they had to sing with a brighter tone with more “squillo.”

The music director commented on Ian Roach Hall having a good acoustic in particular, “dry enough and had enough clarity for us to be able to comfortably do all of the Whitacre[4].” Most respondents commented that most or all of the pieces performed worked well in the space.

4.2.8 Dorothy Pizzey Centre (DPC)

The choir put on a short performance at the DPC for the students at St Catherine’s School on the morning[5] of 5 December. This venue is a multi-purpose school auditorium which doubles as a gym. The histogram and boxplots of subjective data from the singer questionnaires is shown in Figure 13.

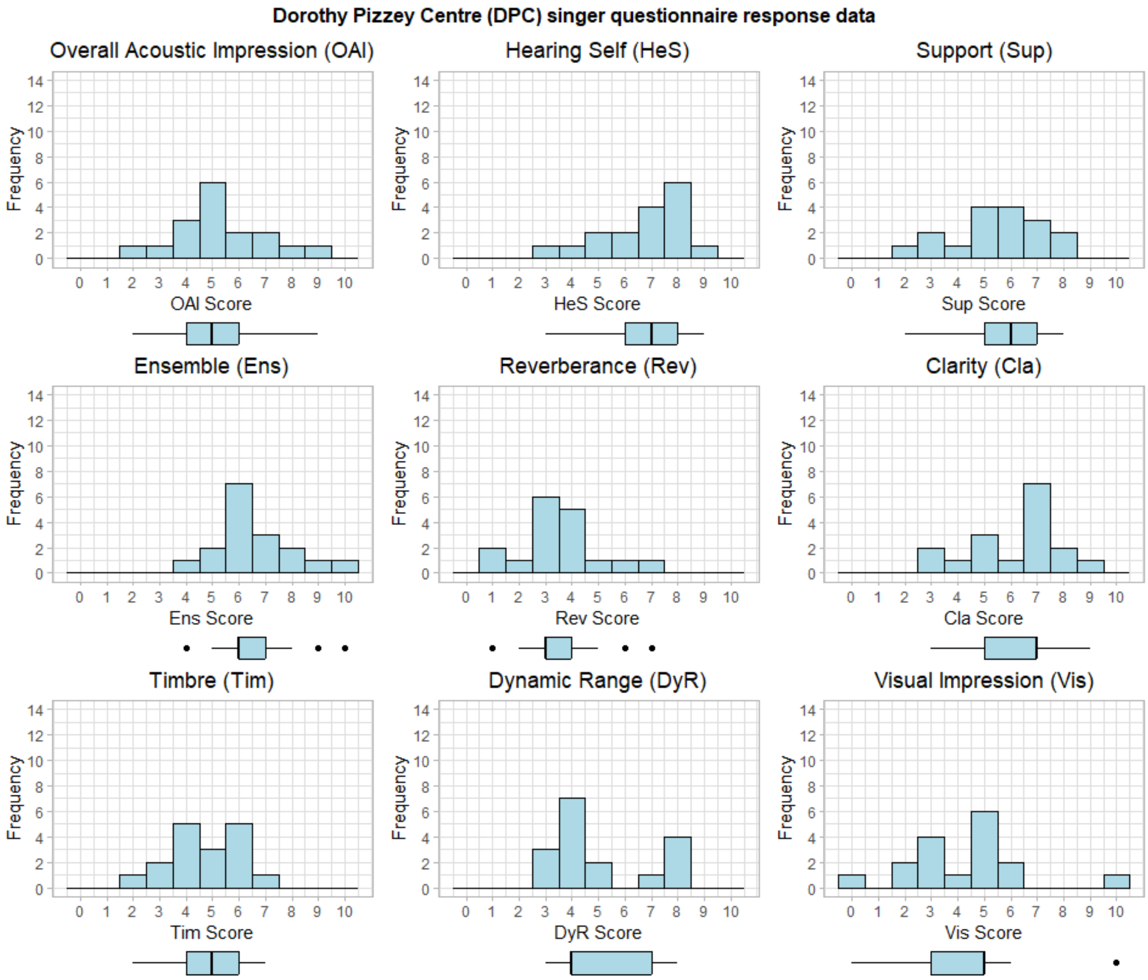


Figure 13: Histogram and boxplots of DPC singer questionnaire responses

---

[4] *The City and the Sea* by Eric Whitacre performed by NZ Youth Choir youtu.be/gOGqTCMl5_o?si=MLUL5vaU_-UfJqVA

[5] A Haiku from a Soprano: *I really hate the morning | Even in a school | I’m longing for a soft bed*

DPC was the third multi-purpose school hall that the choir performed in on the tour. Rather than use the elevated stage, the choir performed standing at floor level and were closer to the audience area. The venue had the lowest median ratings for OAI, Rev, DyR and Vis, and amongst the lowest for HeS.

A number of comments indicated the sopranos and basses could be heard more prominently, with a small number indicating that tenors and basses were more difficult to hear.

Similar to TFC, the respondents thought the venue was acceptable but not the most suitable for choral music. Many indicated that the Māori pieces including 'Ko ngā waka ēnei' and 'Kua Rongo' worked well in this space, and other pieces which had a faster tempo. A Bass 2 attributed this to the "more minimal acoustic" of the space.

During acoustic testing, a very noticeable flutter echo was observed in the space. However, there were no comments from the respondents thar referred to it, and it may have not been noticeable during singing.

4.2.9 Christ Church St Laurence (CSL)

The full choir reassembled in Sydney and performed a 1-hour lunchtime concert in CSL on 14 December. This building is an Old Colonial Gothick Picturesque and Victorian Free Gothic historic church of sandstone construction. The histogram and boxplots of subjective data from the singer questionnaires is shown in Figure 14.

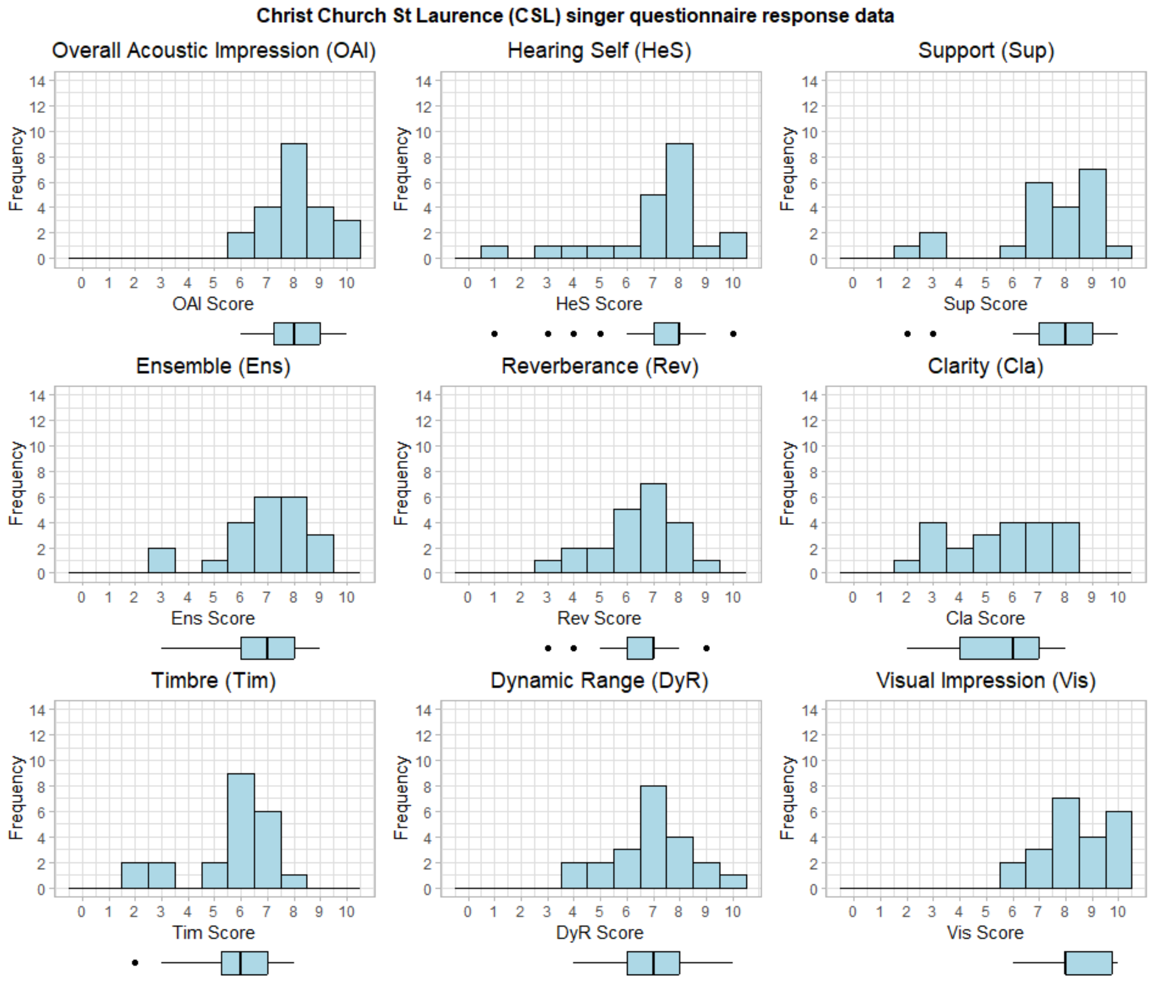


Figure 14: Histogram and boxplots of CSL singer questionnaire responses

The median rating for Sup was amongst the highest across the venues, alongside high median ratings for OAI, HeS, Ens, Rev and DyR. CSL was also arguably the highest rated for Tim, interpreted as having the "warmest" or "mellowest" room response.

There were a number of comments that the sopranos could be heard more prominently. There was a lesser number of comments that the altos and basses were more difficult to hear, including a Bass 2 that noted they felt the need to sing up more with “more cut and resonance.” Another Bass 2 noted that it was easy to sing loud, but harder to sing softly.

A Bass 1 commented that they tried to sing with more consonants while maintaining energy on the vowels, and two Soprano 1s noted the need keep their vowels “tall and bright” or “rounder.”

An Alto 1 noted that the reverberation felt “very thick” and “short,” while an Alto 2 noted that the longer reverberation may have contributed to the more rhythmic pieces feeling out of time.

More than half the respondents commented that ‘Hymn to St Cecilia’ worked really well in the space. However, this was the only occasion this was presented on the tour, and so there were no other recent performances to compare it to.

4.2.10 Sydney Opera House, Concert Hall (SOH)

The NZYC were a guest choir at the Gondwana Choirs’ ‘Voices of Angels 2022’ concert on the evening of 14 December. The choir performed a short set of approximately 20 minutes, and participated in a number of massed items with the Gondwana National Choirs, The Sydney Children’s Choir and Hunter Singers.

The venue is a modern expressionist concert hall with construction completed in 1973, and it is a culturally significant building. The histogram and boxplots of subjective data from the singer questionnaires is shown in Figure 15.

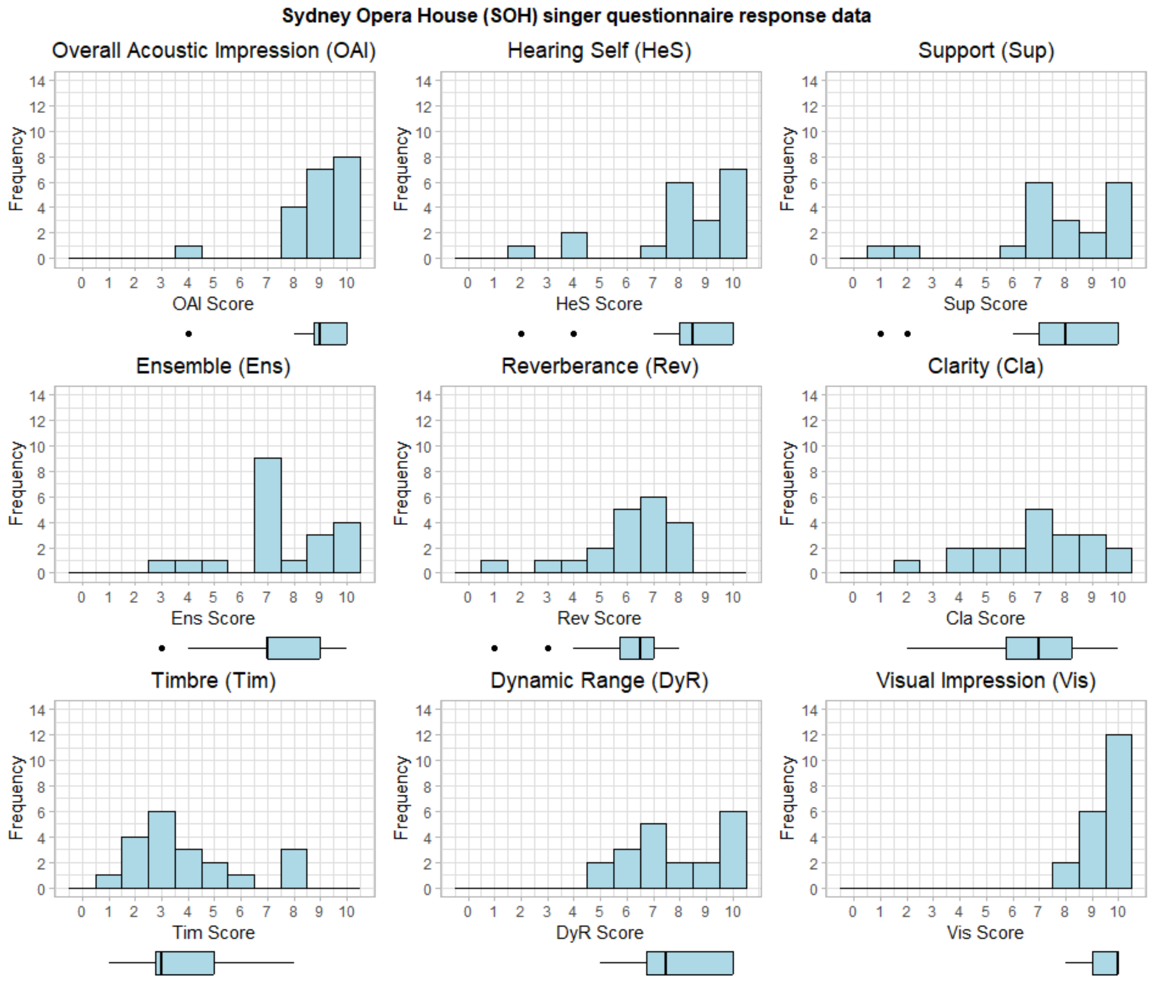


Figure 15: Histogram and boxplots of SOH singer questionnaire responses

The SOH was rated amongst the highest for OAI, Vis and HeS, and amongst the highest for Sup. It is possible that this venue scored particularly highly due to its cultural significance, which a Tenor 2 also commented on. A Soprano 2 commented that the space felt like a “fine-tuned instrument.”

The SOH has the biggest room volume compared with all the venues performed in on this tour, or any venue that this iteration of the NZYC has performed in domestically in NZ. However, many respondents noted the ease in which they could hear themselves and others on stage, all while generally maintaining balance of the voice parts.

A small number of comments noted the basses were more difficult to hear, and the sopranos and altos were heard more prominently. Two respondents commented on the ability to hear across the choir depended on how close the singers were positioned, as the SOH stage is designed for a full-sized symphony orchestra and quite large. Three respondents noted the need to sing with increased consonant strength.

An Alto 1 noted that the reverberant field felt “all encompassing.” However, she noted a “strange reverb” made the singers behind her sound “very processed/recorded,” and suspected that this was due to reflections from the side as opposed to from the back of the hall behind the audience. One Tenor 2 noted “strong echoes” from the back of the hall, likely a result of the large longitudinal dimension compared to the other venues.

4.3 Subjective Respondent Results

4.3.1 Spearman correlation results

Scatter plots were generated between each subjective metric, and a local polynomial regression with a span of 1 was fitted. In general, relationships tended to have greater linearity at higher scores, and a larger spread of data for lower scores.

It is hypothesised that there is a monotonic relationship between subjective variables, but not necessarily linearity. Therefore, the Spearman rank-order correlation has been used to analyse the data, rather than the Pearson product-moment correlation which measures strength of linearity.

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 8.

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[6].

Table 8: Grading of Spearman correlation coefficients

Range of correlation $\lvert r_s \rvert$	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

---

[6] The exact p-value cannot be calculated due to overlapping data points or “ties.” This is unavoidable due to the nature of interval data.

The calculated Spearman correlation coefficients are summarised in Table 9, with the strength of correlation colour-coded according to the ranges in Table 8. Correlations with p-values greater than 0.05 have been assigned no correlation. No outliers have been excluded in calculating the coefficients.

The Spearman rank-order correlation shows that most metrics have weak to moderate correlation. Due to the slight difference in response rate across the venues, it is possible that the data is skewed towards respondent tendencies with a higher response rate. With the data collected, it is not possible to determine the variation of sample means within each venue. The variation in respondent rates is 36%, so it may be assumed that the effect, if any, would be small. It is possible to weight the responses to ensure are more even contribution from any individual.

Table 9: Spearman correlation coefficients within subjective metrics

r_s	OAI	HeS	Sup	Ens	Rev	Cla	Tim	DyR	Vis
OAI	1	0.31	0.49	0.47	0.37	0.23	0.00	0.48	0.56
HeS		1	0.25	0.31	0.01	0.34	–0.18	0.19	0.17
Sup			1	0.45	0.32	0.08	0.12	0.31	0.29
Ens				1	0.15	0.34	–0.02	0.28	0.18
Rev					1	–0.09	0.08	0.19	0.34
Cla						1	–0.29	0.33	0.11
Tim							1	–0.11	0.01
DyR								1	0.42
Vis									1

4.3.2 Interpretation and discussion of correlations

A selection of correlations including those with the greatest r_s have 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.

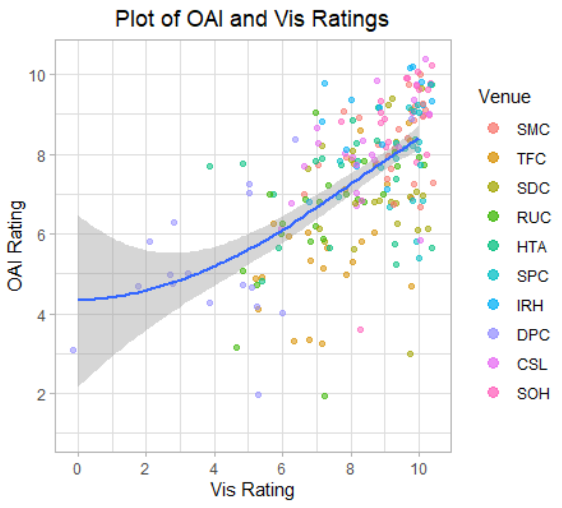


Figure 16: Scatterplot of OAI and Vis, $r_s = 0.56$
(jitter bin width of 1, LOESS fit span of 1)

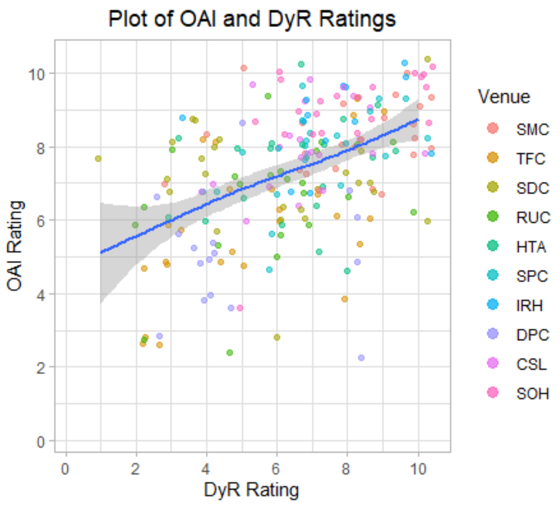


Figure 17: Scatterplot of OAI and DyR, $r_s = 0.48$
(jitter bin width of 1, LOESS fit span of 1)

Interestingly, the strongest correlation is observed between OAI and Vis (Figure 16). 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. Kim et al. [39] theorised that visual impression had a greater influence on subjective ratings when compared with responses from instrumentalists in the same venues.

OAI is also moderately correlated with DyR (Figure 17), which has likely influenced the moderate correlation between Vis and DyR. Likewise, this correlation with Vis is likely due to the types of venues in the sample rather than direct effects.

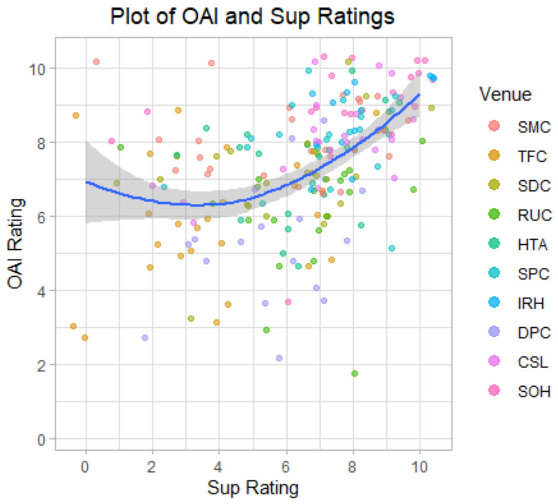


Figure 18: Scatterplot of OAI and Sup, $r_s = 0.49$
(jitter bin width of 1, LOESS fit span of 1)

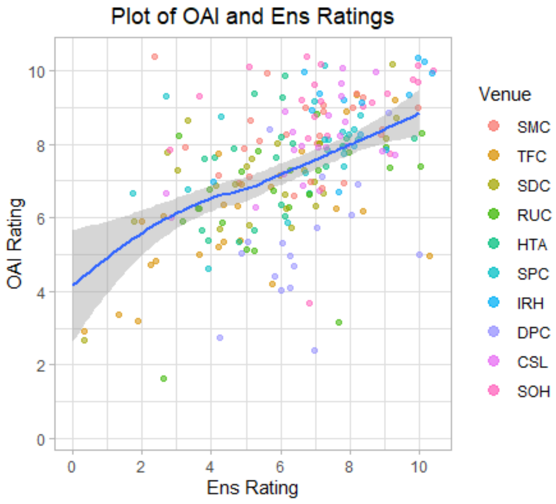


Figure 19: Scatterplot of OAI and Ens, $r_s = 0.47$
(jitter bin width of 1, LOESS fit span of 1)

OAI is moderately correlated with Sup and Ens (Figure 18 & Figure 19), and to each other (Figure 20). This was as expected, and supports the idea that singers have SOR preferences for spaces that allow for a balance of how well their voice is received by the room, with how well they can hear the others in the choir [19].

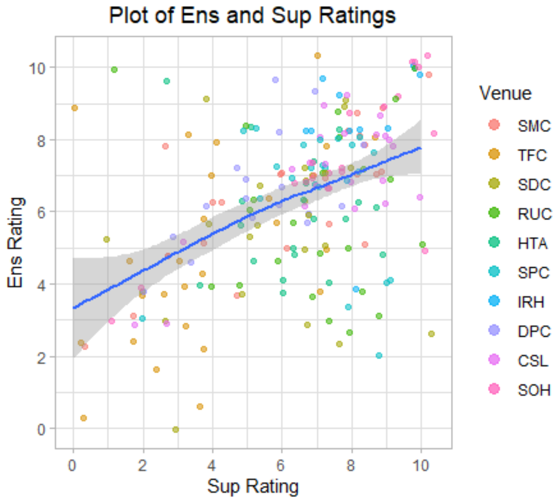


Figure 20: Scatterplot of Sup and Ens, $r_s = 0.45$
(jitter bin width of 1, LOESS fit span of 1)

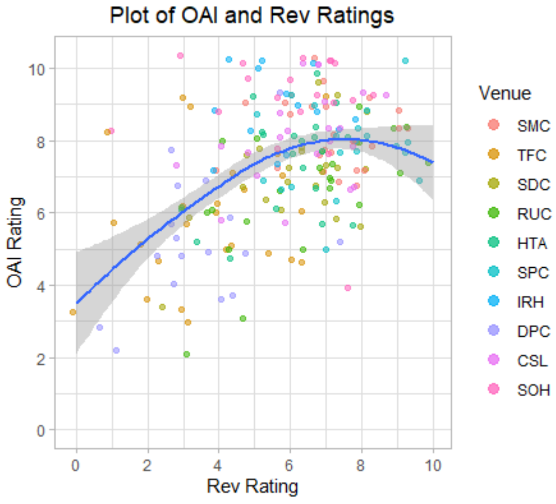


Figure 21: Scatterplot of OAI and Rev, $r_s = 0.37$
(jitter bin width of 1, LOESS fit span of 1)

Rev has some weak and very weak correlations with other metrics, and is most strongly correlated with OAI (Figure 21). 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. Below OAI ratings of 7 and Rev ratings of 5, there appears to be a moderate monotonic correlation.

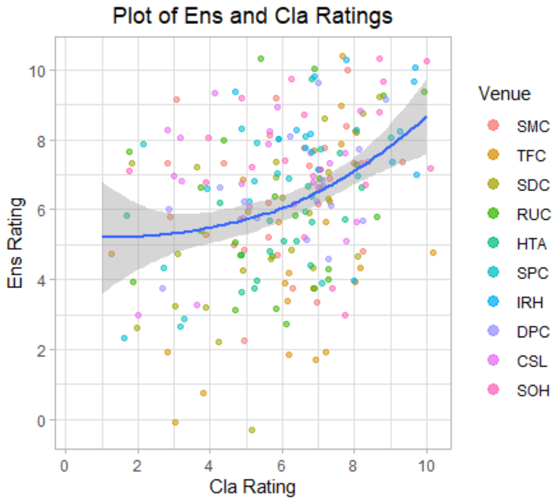


Figure 22: Scatterplot of Ens and Cla, $r_s = 0.34$
(jitter bin width of 1, LOESS fit span of 1)

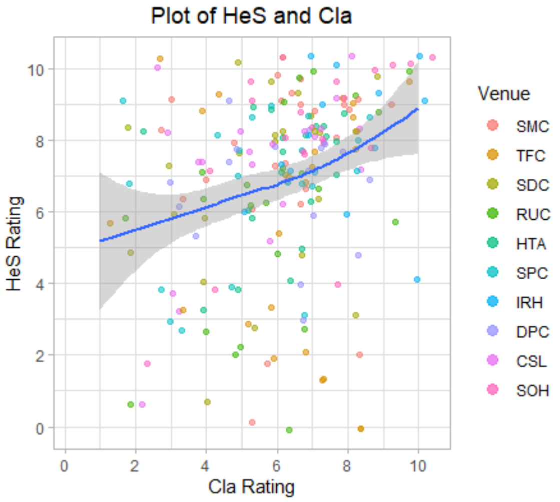


Figure 23: Scatterplot of HeS and Cla, $r_s = 0.34$
(jitter bin width of 1, LOESS fit span of 1)

Ens is weakly correlated with Cla (Figure 22), and it was anticipated that clearer consonants heard from others in the choir would aid keeping in tempo. Notably, this does not translate to a correlation of Sup and Cla, and indicates that singers may not be listening for how the room supports or amplifies their own consonants.

In contrast, HeS is also weakly correlated with Cla (Figure 23), noting that most HeS ratings were at least 4. This implies that singers may listen for their own consonants, specifically the direct sound, to be able to hear themselves among other singers. The data also indicates that there were no venues most respondents found it particularly difficult to hear themselves.

HeS was found to have a weak to very weak correlation with most other metrics. It was anticipated that there would be a stronger correlation with HeS and DyR.

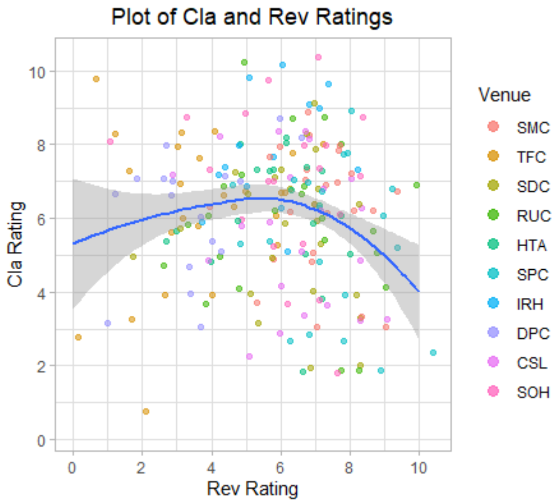


Figure 24: Scatterplot of Cla and Rev, $r_s = -0.09$
(40% jitter within bin width of 1, LOESS fit span of 1)

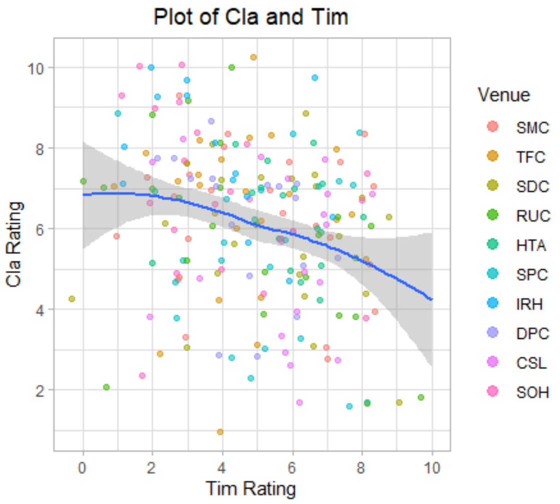


Figure 25: Scatterplot of Cla and Tim, $r_s = -0.29$
(40% jitter within bin width of 1, LOESS fit span of 1)

It was anticipated that there would be a negative correlation of Cla and Rev (Figure 24), 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. Likewise, spaces with very short reverberation times, such as those not designed for music, may give additional insight.

There is a weak correlation between Cla and Tim (Figure 25) and also HeS, suggesting that choral clarity may also have a significant frequency component in addition to the time component. This can be interpreted as a room with higher perceived brilliance and brightness, would indicate a higher degree of clarity and ability to hear oneself. This would be expected as the frequency content of consonants are generally of higher frequency in the sung languages in the repertoire.

There were low rates of agreeance on what pieces suited the venues and which ones didn’t. The author noticed that respondents were answering with pieces that were or weren’t performed well (e.g., pieces deemed not suitable when the choir made mistakes), rather than make the judgements based on the acoustic experience.

Respondents also tended to answer the prompt on echoes by pointing out the extraneous noise sources, rather than acoustic room effects.

4.4 Acoustic Room Measurements

The 3DRIR measurements were analysed with the software package IRIS 2.0. A 3-D sound intensity vector plot for each venue is included in Appendix E.

Within each performance, members of the choir do not stand in the same positions between each piece. In some circumstances, the formation was not the same across the venues for a particular piece of music. It is assumed that each singer would have stood at multiple locations on the stage and would have some idea of the variation of acoustic response across the stage.

For this reason, it is considered reasonable to average the 1-metre S-R distance measurements (A1, A2, B1, B2, C1, C2) and the cross-stage measurements (A3, B3). Time- (RT) and ratio-based (J_{LF}, BR, TR) metrics have been arithmetically averaged, and energy-based (C, ST, G) metrics have been logarithmically averaged. The bass and treble ratios have been calculated based on each set of averaged values. These averaged results, including the octave-band data, are found in Appendix E.

Upon interrogation of the averaged data sets, it is noted that the 1-metre and cross-stage metrics are generally quite similar, apart from the clarity metrics as expected. Therefore, the data has been further consolidated by arithmetically or logarithmically averaging these as appropriate, and the mid-frequency values are presented in Table 10. These values have been used for further statistical analysis as discussed in Section 4.5.

The range of G metrics at 1 metre source-receiver distances are generally close to the just-noticeable difference range, and so have been excluded from the results.

Note that due to the time limitations on tour, acoustic measurements at CSL were conducted at a later date on 11 July 2023 by colleagues from the MDA Sydney office. Measurements were taken by a similar IRIS Mini kit. It is assumed that there were negligible changes to the acoustic properties of the space between the date the performance and the date of measurement.

It is generally understood when considering reverberation time in a larger volume, that the perceived reverberance would be lower when considering the same RT in a smaller room. Commonly used charts for RT plotted against a logged volume axes generally indicate linearly increasing target reverberation times. An example from Harris’ *Handbook of Noise Control* [40] is shown in Figure 27. It would be expected that subjective reverberance would be influenced by correcting RT with volume.

Table 10: 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_{20} (s)	2.53	1.36	1.82	1.59	1.79	2.07	1.43	2.44
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) *	-12.3	-12.2	-12.8	-7.8	-13.5	-14.9	–	-10.1
$C_{80\ (1m)}$ (dB)	11.8	12.8	12.6	8.0	11.9	14.5	12.0	10.1
$C_{80\ (cross)}$ (dB)	1.4	3.1	2.6	0.1	2.7	3.2	4.4	-1.4
$C_{50\ (1m)}$ (dB)	10.9	11.3	11.7	6.1	11.1	13.2	10.0	8.9
$C_{50\ (cross)}$ (dB)	–0.1	1.6	1.4	-2.2	0.6	1.7	2.0	-3.5
G (dB) †	10.5	10.8	12.1	14.8	10.0	9.8	11.1	13.4
G_{Early} (dB) †	8.2	9.1	10.2	11.8	8.2	8.2	9.6	9.6
G_{Late} (dB) †	6.7	5.8	7.4	11.7	5.5	4.9	5.4	11.0
LF †	0.07	0.05	0.06	0.16	0.05	0.05	0.04	0.07
Calculated parameters								
BR	0.94	1.24	0.77	0.80	0.97	0.98	0.85	0.79
TR	0.77	0.84	0.82	0.86	0.82	0.78	0.97	0.86
$T_{30}/\log_{10}V$ ($s/\log_{10}m^3$)	0.65	0.38	0.51	0.56	0.49	0.53	0.43	0.68

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

† Due to limitations in equipment, the strength and lateral fractions shall be considered as relative only.

The RTs were plotted against volumes with a logarithmic x-axis (Figure 26). It’s noted that most of the church venues lie near or above the “Catholic church” line in Figure 27, with the school auditoriums comparable to the “Protestant church” line.

Other commonly used charts such as that provided by Egan in *Architectural Acoustics* [41] indicate preferred reverberation time ranges without reference to room volume (Figure 28). However, Egan notes that “In general, large rooms should be nearer the upper end of the reverberation time ranges than smaller rooms of the same type.” All measured church-type venues have RTs that fall within the “Secular Chorus” and “Liturgical (chorus)” preferred ranges, and both school auditoriums are on the lower end of the “High School Auditoriums” range.

Unfortunately, concert logistics did not allow for measurements to be taken at IRH and SOH.

The acoustics of the IRH (and the James Forbes Academy it is part of) was designed by Arup acoustic engineers and the inaugural performance[7] in the venue was in 2005. It’s understood that commissioning acoustic measurements were undertaken, but the results could not be procured.

---

[7] Warmth, intimacy and excitement at inaugural concert www.scotch.vic.edu.au/greatscot/2005mayGS/05roach.htm

It is noted that the acoustician Jordan [42] envisaged the Sydney Opera House Concert Hall to have a reverberation time of “1,8 to 2,0 sec. for symphony concerts and 1,6 to 1,8 sec. for grand opera” (see Figure 110 in Appendix F10). Following completion, Jordan’s measurements [43] showed that the mid-frequency EDT was approximately 2.5 seconds unoccupied and 2.1 seconds with a capacity audience. The Concert Hall acoustic refurbishment that was completed in mid-2022 mainly focused on the overhead reflectors and the stage-side diffusers [27]. This likely changed the characteristics of the early reflections on the stage, but are unlikely to have significantly changed the reverberation time.

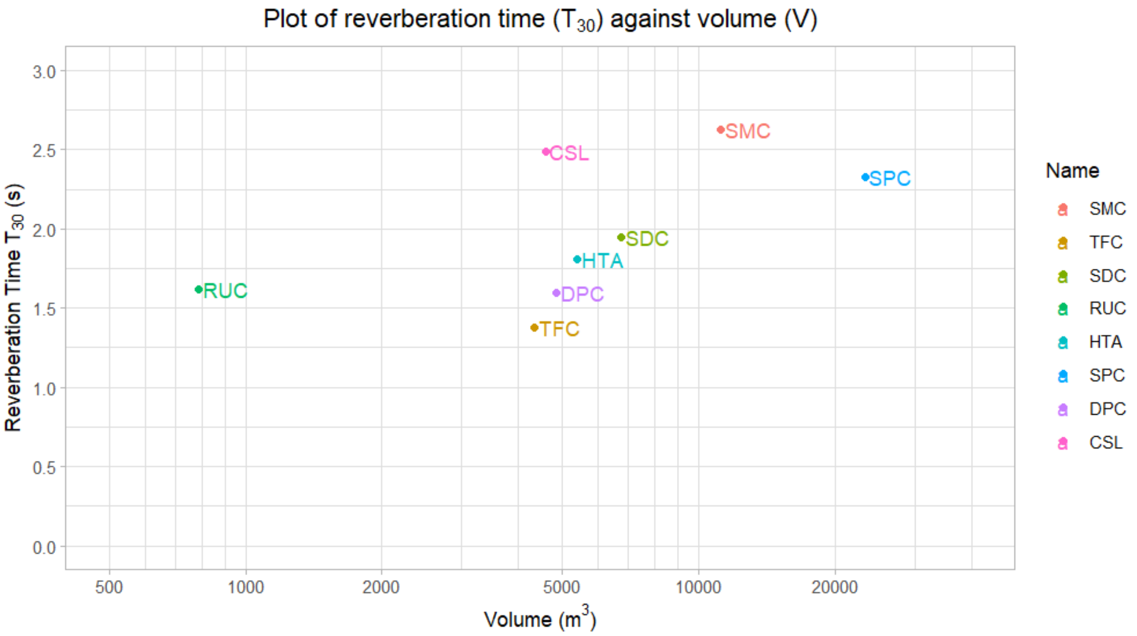


Figure 26: Plot of reverberation time against volume of measured venues

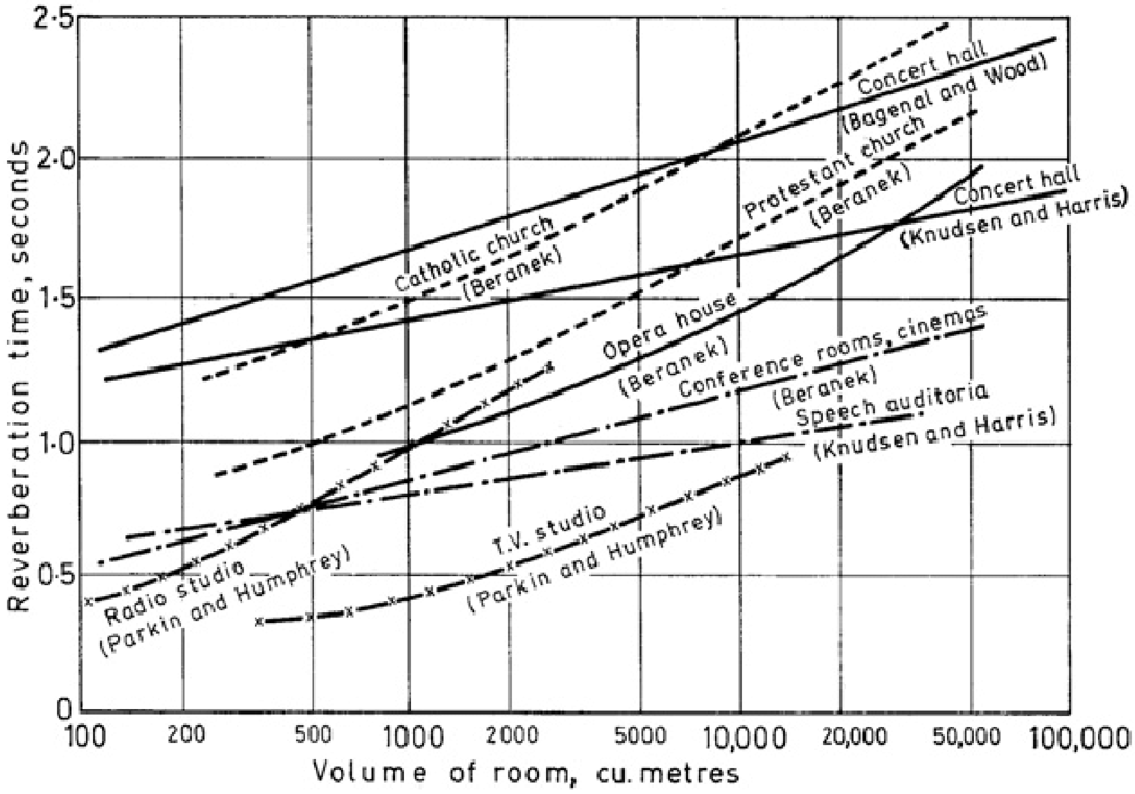


Figure 27: Variation of optimum reverberation time with volume (Source: *Handbook of Noise Control* [40])

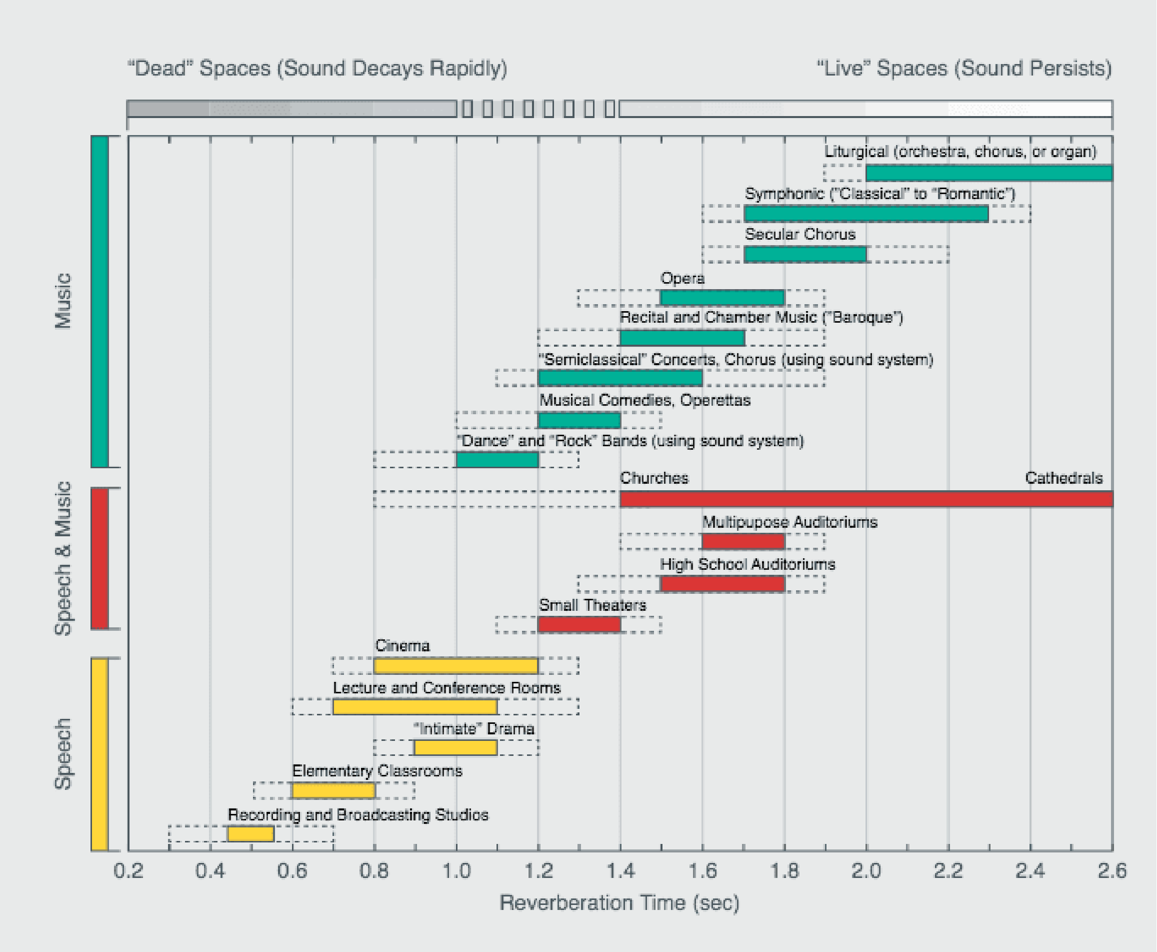


Figure 28: Preferred ranges of reverberation time at mid-frequency
(Source: online.berklee.edu/takenote/acoustics-in-music/ adapted from *Architectural Acoustics* [41])

4.5 Subjective and Objective Correlation

4.5.1 Spearman correlation results

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 determine actual room response. The analysis is based on the full set of questionnaire data and the averaged acoustic measurements as summarised in Table 10 overleaf.

The full set of Spearman correlation coefficients (r_s) are summarised in Table 11 and graded in accordance with the criteria described in Section 4.3.1. Coefficients for T_{20} and T_{30} were within 0.01 units, so only T_{30} coefficients have been included.

Each datapoint has been treated as an individual observation, and the venues have not been weighted.

4.5.2 Interpretation and discussion of correlations

A selection of notable correlations have 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" within a bin width of:

- half the difference of the largest difference between 1m and cross-stage measurements for time-based measurements (RT), and metrics derived from these (BR, TR); or
- 0.3 dB for energy-based measurements (ST, C_{80}), in accordance with the estimated standard deviation in ISO 3382-1:2009 Annex C

Bin heights remain at 1 for the subjective metric on the y-axes. The shaded areas around the LOESS fit line represents its 95% confidence interval. Note that the boxplot outlier points have been removed to avoid visual confusion with the jittered datapoints.

Table 11: Spearman correlation coefficients of subjective and objective measures

r_s	OAI	HeS	Sup	Ens	Rev	Cla	Tim	DyR	Vis
EDT	0.51	0.12	0.33	0.18	0.47	–0.07	0.15	0.36	0.38
T_{30}	0.53	0.16	0.30	0.20	0.53	–0.08	0.14	0.39	0.50
$T_{30}/\log_{10}V$	0.43	0.09	0.38	0.21	0.49	–0.09	0.09	0.31	0.32
$C_{80\,(1m)}$	–0.12	–0.01	–0.25	–0.10	–0.15	0.01	–0.04	–0.09	0.15
$C_{80\,(cross)}$	–0.27	–0.05	–0.27	–0.08	–0.29	0.06	–0.09	–0.15	–0.14
$C_{50\,(1m)}$	0.05	–0.04	–0.16	–0.10	0.05	–0.02	0.03	0.01	0.33
$C_{50\,(cross)}$	–0.28	–0.04	–0.28	–0.08	–0.29	0.04	–0.10	–0.17	–0.11
ST_{Early}	–0.38	–0.12	–0.09	–0.04	–0.34	0.04	–0.16	–0.27	–0.44
ST_{Late}	–0.16	–0.07	0.03	0.01	–0.18	0.03	–0.09	–0.12	–0.34
G	–0.17	–0.08	–0.09	0.00	–0.11	–0.04	–0.02	–0.18	–0.27
G_{Early}	–0.30	–0.11	0.01	–0.07	–0.21	–0.03	–0.02	–0.28	–0.37
G_{Late}	0.07	–0.01	0.17	0.00	0.13	–0.04	0.03	0.00	–0.01
J_{LF}	0.17	0.01	0.20	0.03	0.23	–0.04	0.04	0.10	0.10
BR	–0.08	–0.02	–0.22	–0.08	–0.15	0.10	–0.11	0.02	0.02
TR	–0.32	–0.12	–0.01	0.03	–0.39	0.01	–0.05	–0.28	–0.53

Reverberation time

The reverberation time metrics, in particular T_{30}, had the strongest correlation with Rev (Figure 29). This indicates that the respondents were able perceive the difference in reverberance between the venues with the greatest consistency compared with other metrics ($r_s = 0.53$).

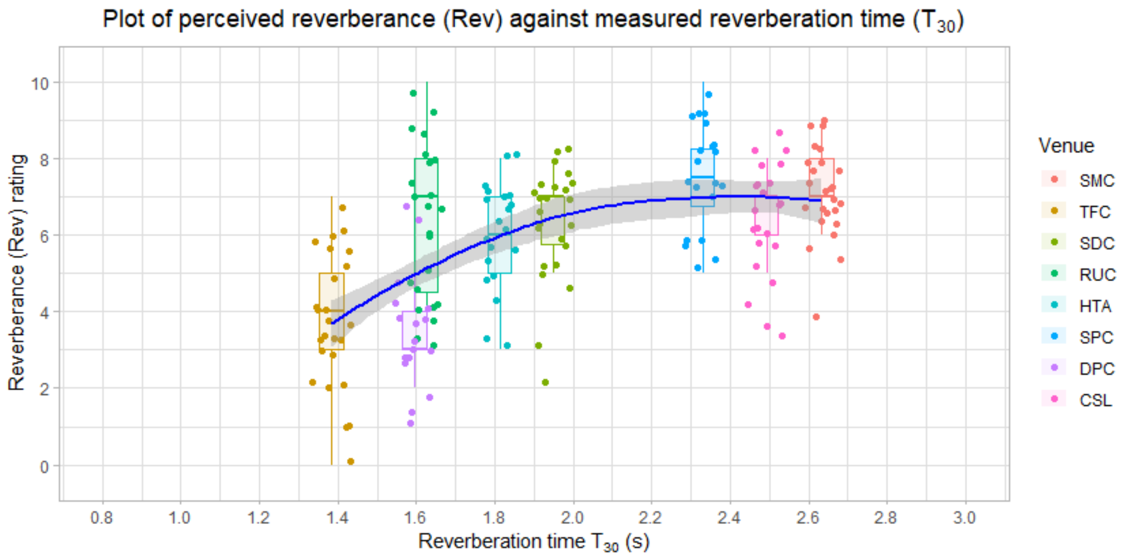


Figure 29: Scatterplot with boxplot of Rev vs. T_{30}, $r_s = 0.53$ (jitter bin width of 0.05, LOESS fit span of 1)

Personal experience as a chorister indicates that reverberance is best observed at the cut-off of a loud note. This allows for the greatest decay over a longer period of time where it can be observed, where the effects are not masked. Most notably, this occurs several times in the piece 'Elijah Rock.' This also allows for the effect to observed when the choristers are not actively singing, and so there is reduced masking effects during observation of the decay.

It's also noted that the approximate reverberation time of SOH (2.1–2.5 secs 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 time 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, it indicates that there were no venues for 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. This range is on the upper end of Egan's preferred reverberation times for "Liturgical" music (Figure 28), which may have been influenced by the selection of repertoire performed. 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. [13] for which a space with a shorter reverberation time of 1.77 seconds was preferred over 4.79 seconds by the singers.

A reverberation time of 4.79 seconds is much higher than what would typically be sought in a venue for contemporary performances of choral music. Reverberation times affect the type of pieces and the tempo at which they are "best" performed at. 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.

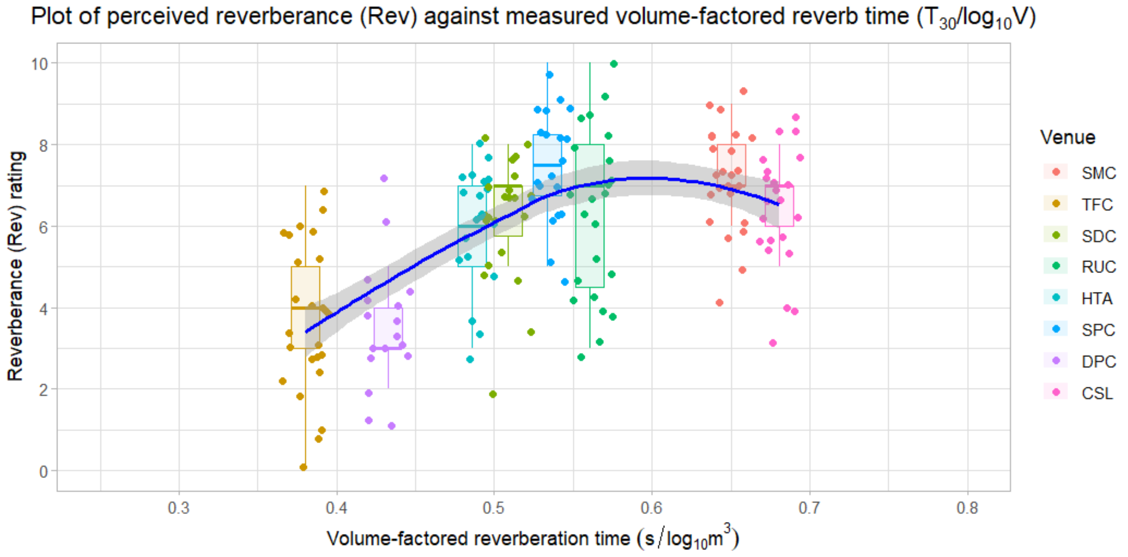


Figure 30: Scatterplot with boxplot of Rev vs. $T_{30}/\log_{10}V$, $r_s = 0.49$ (jitter bin width of 0.015, LOESS fit span of 1)

Notably, the strength of the reverberation time correlation is slightly weakened when room volume is accounted for ($r_s = 0.49$). Additional analysis and comparison with MDA internal tools which use both logged volume and reverberation time further weakened the correlation. This indicates that the singers' perception of the 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 30).

The reverberation time metrics had a comparably strong correlation with OAI (Figure 31). The results support Marshall and Meyer's findings which indicate that singers respond primarily to reverberation as opposed to early reflections [10].

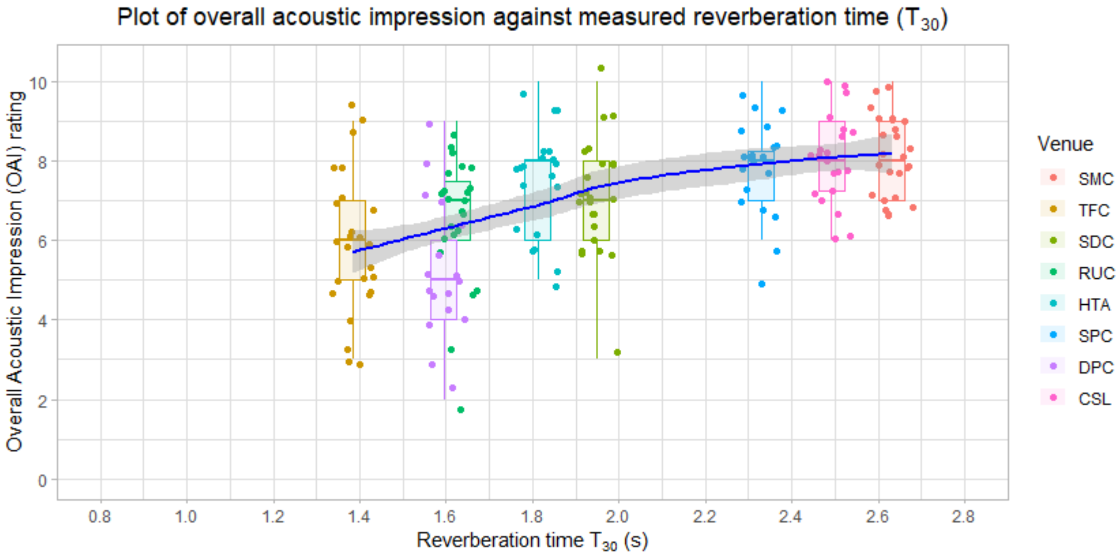


Figure 31: Scatterplot with boxplot of OAI vs. T_{30}, $r_s = 0.53$ (jitter bin width of 0.05, LOESS fit span of 1)

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 31 implies that these venues would have reverberation times above 2.5 seconds, more reverberant than all 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.

Clarity

It was hypothesised that Ens or Cla would correlate with the clarity metrics (C_{80} and C_{50}), but this is not supported by the data ($|r_s| < 0.11$). There were no statistical correlations of the Cla subjective metric with all measured acoustic parameters ($|r_s| < 0.10$).

Excluding reverberation time, Sup appears to correlate the best with the clarity metrics C_{80} and C_{50} when measured across the stage ($r_s < -0.26$). This indicates that lower levels of clarity from other singers in the choir contribute to higher levels of perceived support. This may indicate preference from the singers' perspective to hear late reverberant levels from other singers to add to the sense of support, rather than direct or early reflections from other singers to maintain sense of ensemble.

The inverse relationship of Rev and the cross-stage clarity metrics is expected ($r_s = -0.29$), with the understanding that an increase in reverberance would decrease clarity. However, it's noted that OAI is less strongly correlated with the clarity metrics compared to reverberance. This is interpreted as the decrease in clarity was an acceptable trade-off for high reverberation levels in the sample of venues.

Early stage support

It was anticipated that the stage support parameters would be best correlated with a combination of HeS, Sup and Ens. However, this is not statistically supported by the data.

It was hypothesised that there would be a correlation between HeS or Ens with ST_{Early}, but there is a lack of statistical evidence to support this ($|r_s| < 0.13$). Furthermore, it appears that there is only one very weak correlation between HeS and T_{30} ($r_s = 0.16$), and none for all other acoustic metrics assessed.

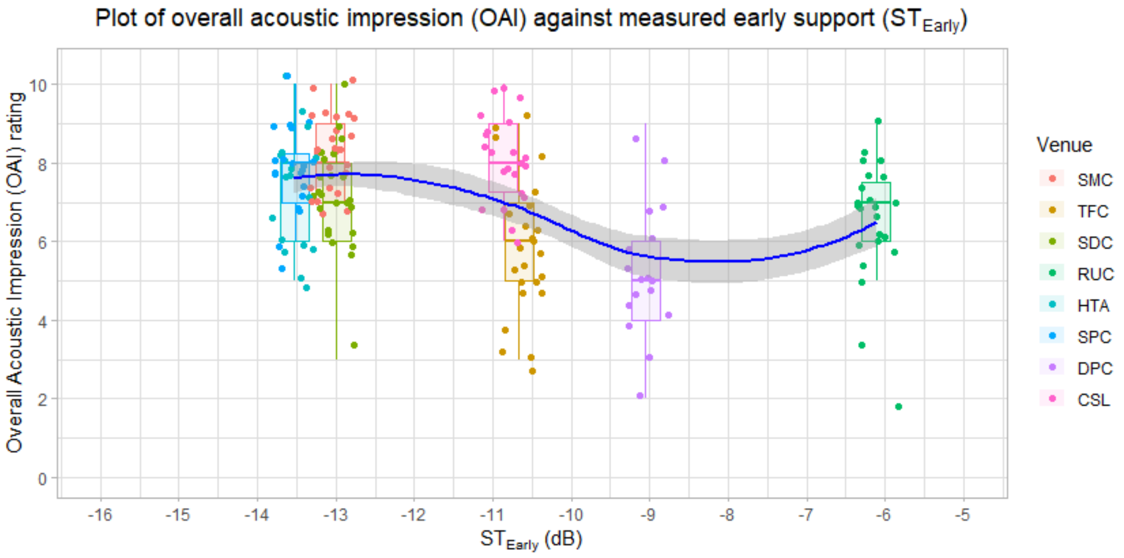


Figure 32: Scatterplot with boxplot of OAI vs. ST_{Early}, $r_s = -0.38$ (jitter bin width of 0.3, LOESS fit span of 1)

OAI (Figure 32) and Rev (Figure 33) are weak to moderately correlated with ST_{Early}. However, interrogation of the scatterplot shows that the weakening of the correlation is highly influenced by the perceived reverberance of RUC. Particularly high levels of ST_{Early} measured at RUC and its low room volume (Figure 26) may contribute to an overly high perception of relative reverberance.

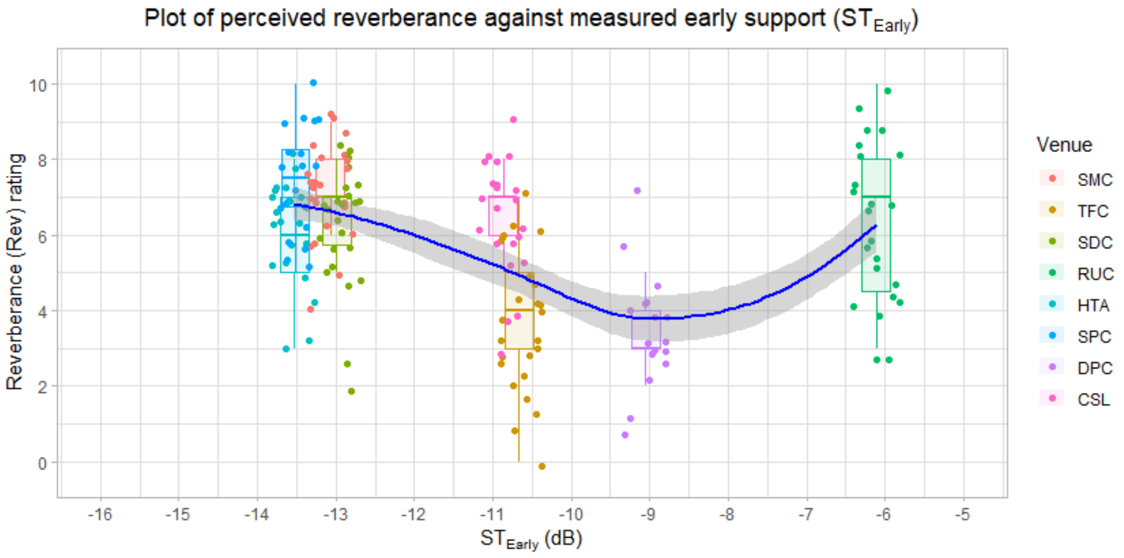


Figure 33: Scatterplot with boxplot of Rev vs. ST_{Early}, $r_s = -0.34$ (jitter bin width of 0.3, LOESS fit span of 1)

It is noted that the ST_{Early} for RUC is outside of the typical upper range of –8 dB presented in ISO 3382-1:2009 Table C.1 (Table 2). When the data for RUC is removed, the r_s increases in magnitude to –0.51 with Rev, indicating a moderate negative correlation between reverberance and ST_{Early}. Low levels of early reflected energy on stage reduces the masking effects on the direct and early sound on the reverberant field, and may allow singers to better observe the reverberant decay effect.

This suggests that unusually high levels of early reflections may be interpreted as an increase in perceived reverberance. This is particularly evident in RUC and visualised in the 3-D sound intensity vector plot (Appendix E4, Figure 42), indicating that ST_{Early} values above the typical upper range of

–8 dB may skew perceived reverberance. It is also likely that high values of ST_{Early} may have negative effects on the ability to hear oneself within the choir above the other voices. This is indicated in the singer comments for RUC but does not appear to be statistically significant in the data (r_s = –0.12).

While not typically encountered in a performance hall or theatre, particularly high levels of early energy may be present in small and moderately reverberant rehearsal spaces. Gade did not intend for the ST parameters to be used in smaller rooms, i.e., "rooms which do not accommodate a full symphony orchestra" [33]. Furthermore, he suggests that the lower integration time of 20 milliseconds for ST_{Early} "must be reduced" if used to assess these rooms.

There does not appear to be a particularly strong trend between OAI and Rev against G_{Early} (Figure 34), and this does not seem to be skewed by particularly high G_{Early} at RUC. Our results indicate that overall acoustic impression is more influenced by ST_{Early} compared to G_{Early}.

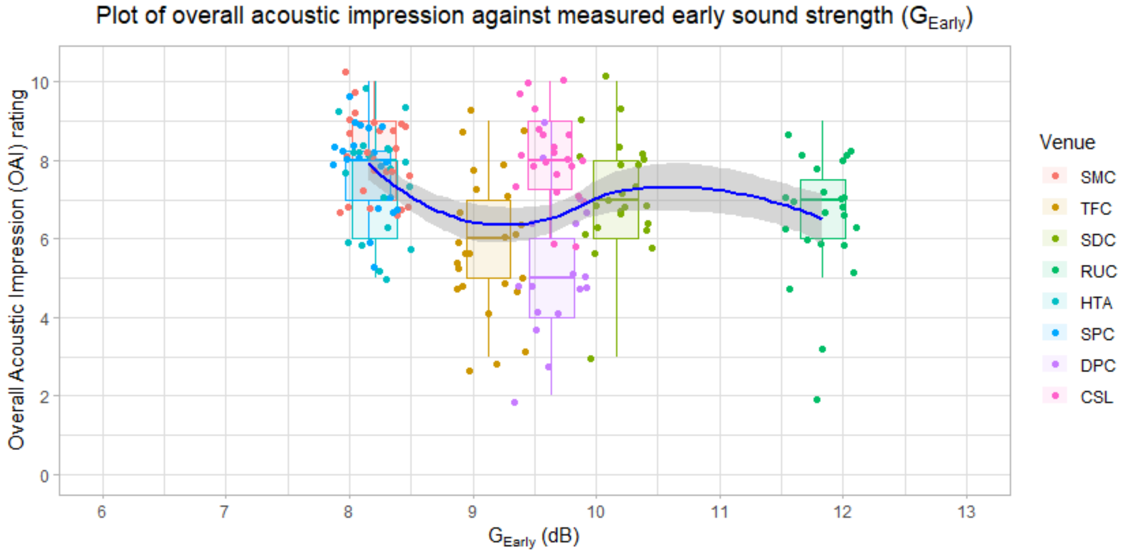


Figure 34: Scatterplot with boxplot of OAI vs. G_{Early}, r_s = –0.30 (jitter bin width of 0.3, LOESS fit span of 1)

Late stage support

A similar but weaker effect is observed between perceived reverberance and ST_{Late} (Figure 35), where the measured ST_{Late} for RUC is above the typical upper range of –10 dB presented in ISO 3382-1:2009 Table C.1 (Table 2). Notably, the LOESS fit line also starts to trend upwards where the ST_{Late} for CSL is very close to the upper range. Note that ST_{Late} for DPC could not be measured reliably and is excluded from the analysis.

The r_s increases in magnitude to –0.27 with the removal of RUC data, and –0.42 when CSL is further removed. This indicates a moderate negative correlation of perceived reverberance to ST_{Late}. However, SMC and TFC have similar levels of measured ST_{Late} of –12.2 dB but have very different values of T_{30} and perceived reverberance, as shown by their deviation from the LOESS line. Noting that ST_{Late} is typically used to describe "perceived reverberance," there is evidence to suggest that ST_{Early} when within the "typical range" has a stronger correlation to this, albeit an inverse one.

The trends observed for ST_{Late} do not appear to be consistent with G_{Late}.

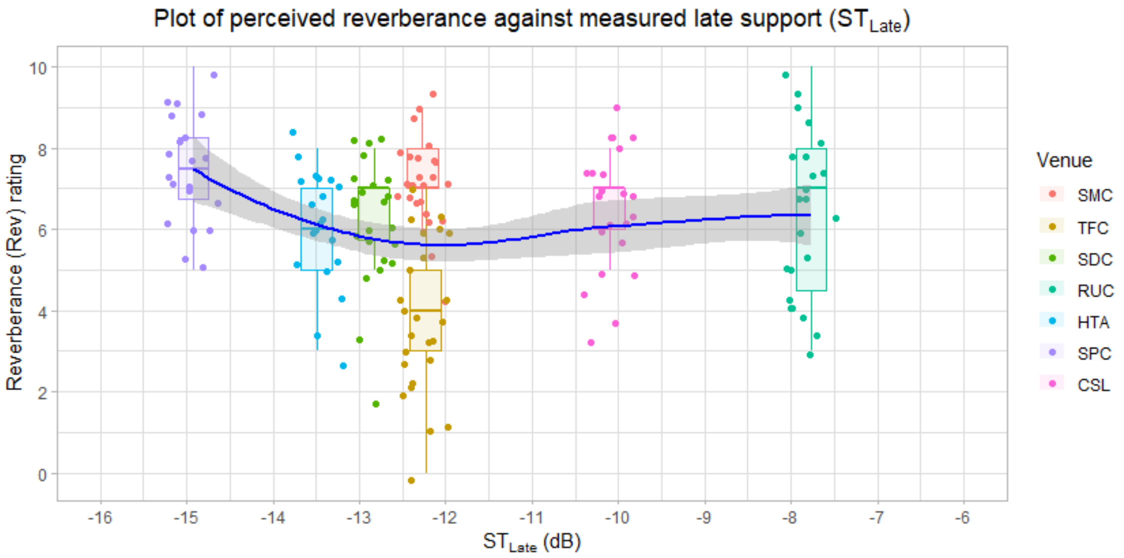


Figure 35: Scatterplot with boxplot of Rev vs. ST_{Late}, $r_s = -0.18$ (jitter bin width of 0.3, LOESS fit span of 1)

Dynamic range

It was hypothesised that DyR would be correlated to sound strength and stage support metrics, and this is weakly supported by the data by a negative correlation of DyR with G_{Early} and ST_{Early} ($r_s < -0.26$). This indicates that high levels of early sound energy received on stage, such as measured in RUC, create conditions which are difficult to achieve large dynamic range in.

Some reoccurring comments on RUC was that many singers tried to sing quieter as they felt the room response was very loud, which increased the difficulty in hearing one's own voice. This indicates that many singers were actively aware of the Lombard effect, which has been shown that it can be consciously resisted by choral singers [17].

Specifically, it may be concluded that it was particularly hard to achieve soft or *pianissimo* dynamics in RUC due to high levels of early sound energy. High levels of relative reverberant sound energy can be observed in the 3-D sound intensity vector plot for measurement B1 (Figure 36).

It is possible that the relationship between the ease of dynamic range variation and G_{Early} or ST_{Early} is not monotonic when extending to spaces with low early energy. Personal experience in a solo context indicates that spaces with low reverberation times and low sound energy on stage may result in a singer feeling the need to "push" or increase their vocal effort. An opposite effect is sometimes observed in a choral context when singers' may reduce their vocal effort when they do not feel adequately supported by other voices. It is likely that the vocal effort to produce a certain dynamic depends on a number of factors such as acoustic environment and SOR, and may vary between individuals.

Lateral fraction

ROH was measured to have by far the greatest lateral fraction ratio (0.16), and this is likely due to the much smaller width of the room compared to the other venues. This can be seen in the 3-D sound intensity vector plot for measurement B1 (Figure 36).

OAI is very weakly correlated with J_{LF} ($r_s = 0.17$) (Figure 37). There is some evidence that indicates preference for greater lateral sound energy, especially at J_{LF} less than 0.08. However, there were no measured venues which had stage J_{LF} between 0.08 and 0.15, and there is limited evidence to show that there is a monotonic relationship within this range.

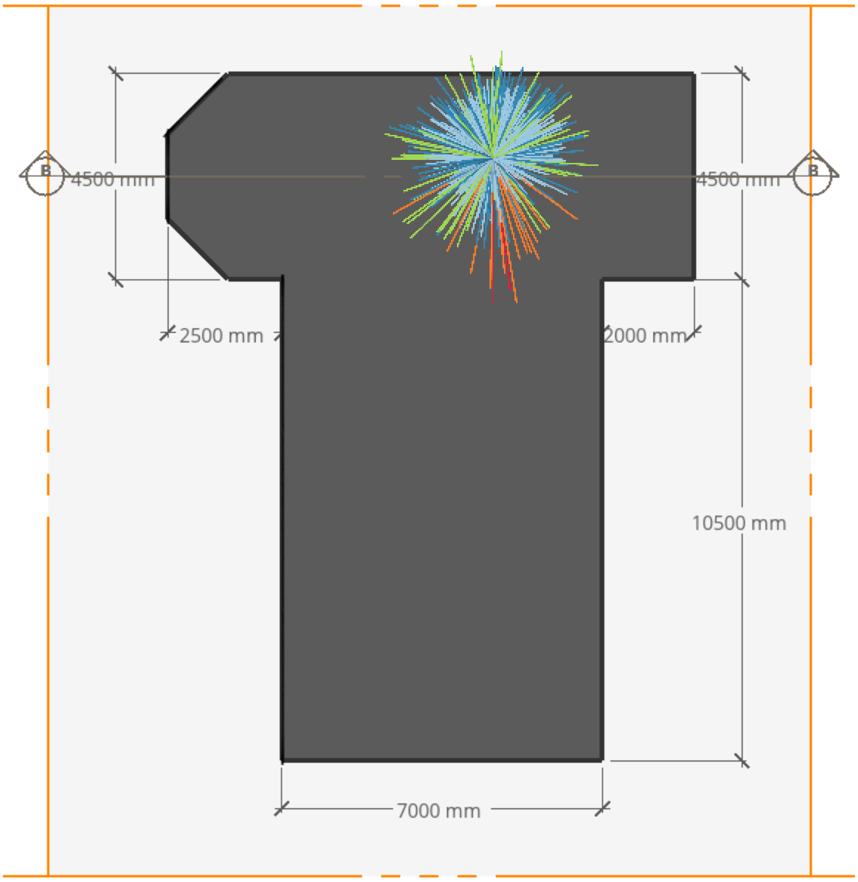


Figure 36: RUC measurement B1 showing high relative reverberant energy and lateral fraction

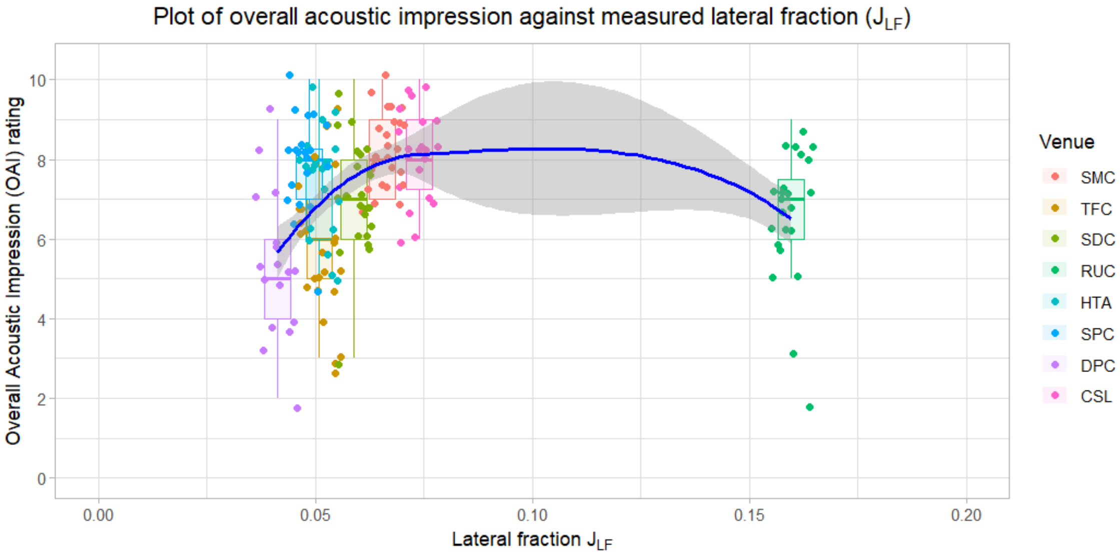


Figure 37: Scatterplot with boxplot of OAI vs. J_{LF}, r_s = 0.17 (jitter bin width of 0.005, LOESS fit span of 1)

There is a slightly stronger correlation between Sup and J_{LF} ($r_s = 0.20$), which is somewhat expected considering that lateral energy likely provides a sense of envelopment for the singers. This also supports the recommendations in literature in favour of side reflectors for singers [10], [36]. However, Sup has a stronger correlation with the reverberation and clarity metrics. This indicates that singer stage support is more strongly determined by reverberation factors based on time rather than direction.

Timbre and balance

There were only very weak statistical correlations of the Tim subjective metric with all measured acoustic parameters ($|r_s| = 0.17$). Although, it is apparent in the survey data that singers are generally aware that rooms have varied response strength across the vocal parts. Furthermore, the many respondents commented that they adjusted the speed or strength of their consonants, or varied the timbre of their voice in response to each space. However, the author notes that many of these conscious changes to vocal production are often instructed by the musical staff who are listening from the audience area.

It was anticipated that Tim would be correlated with BR and TR, particularly as the BR for TFC was considerably higher than the other venues (1.24). It is noted in the comments on TFC that it was the only venue where there was general agreement that the sopranos couldn't be heard more prominently. It is expected that rooms with a higher bass ratio may enable a more balanced sound across the voice sections, particularly when there is less sound energy from lower voice parts. The measured TR for the venues and median ratings were very similar across the spaces, and is unlikely to provide conclusive evidence against any hypothesis.

The audience study by Bonsi et al. [14] showed that the audience was able to judge the timbre in the response of the space with reasonable agreeance with acoustician Raf Orlowski. The interquartile range in timbre of their study is not noticeably different from our data. However, it is likely that an audience would generally be able to better perceive differences in timbre, especially at high frequencies where the voice is particularly directional [10]. A more controlled study using HATS and controlled singer spacing may yield clearer results.

Sup is noted to have a weak negative correlation with BR ($r_s = -0.22$), indicating decreasing perceived support with increased bass response. This effect is inverse to what was expected. It is likely that TFC was rated low for Sup due to a combination of high BR and low reverberation time, noting multiple comments that not one voice part could be heard well. Removing TFC from the analysis indicates no statistically significant correlation between BR and Sup. Based on the singer comments, it is possible that a high BR and higher reverberation time may provide a balanced sound across the voice parts.

5.0 CONCLUSIONS

5.1 Choral Singers' Subjective Perception of Stage Acoustics

The singer response questionnaire results show that the subjective metrics that had the highest correlation with overall acoustic impression were support, ensemble, dynamic range and visual impression. This indicates that singers' assessment of room acoustics is dominated by their perception of variations in temporal characteristics and sound strength, rather than say the frequency characteristics.

The results indicated that no venue performed at was considered "overly reverberant," and venues with higher reverberation times was preferred. Negative effects on clarity were not significant in the sample of venues.

Singers' response to some subjective metrics such as timbre and clarity were highly varied. It is possible that these concepts were not particularly well defined in the questionnaire or understood by the singers. The study would have likely benefited from a glossary of terms that could be provided to the singers alongside the questionnaire.

Some questions were not interpreted and answered as intended. For example, many singers responded to the prompt on "echoes" with references to extraneous sounds such as that from birds or children. Many singers also assigned pieces that "least suited the space" based on mistakes that occurred in the performance that were not likely influenced by the acoustics of the space.

5.2 Acoustic Parameters which Affect Choral Singers' Perception of Stage Acoustics

In this study, 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. This range of preferred reverberation times presented an acceptable trade-off for lower levels of clarity.

Low levels of early stage support ST_{Early} is generally preferred in the typical range ($r_s = -0.51$). Unusually small performance spaces such as may skew perceived reverberance, due to particularly high levels of early sound energy as measured in ST_{Early} and G_{Early} on stage. This may have the effect of masking the reverberant sound decay, and was demonstrated at Ross Uniting Church with a 790 m^3 room volume.

Particularly high levels of early sound energy also has a negative effect of reducing the ability of the singers to achieve large variation of dynamics. In particular, soft dynamics are difficult to achieve when ST_{Early} and G_{Early} on stage are high, and this may be attributed to the Lombard effect.

The results contrast against conclusions in existing literature as noted by van den Braak et. al of a preference for early reflections on stage [11]. However, Marshall and Meyer's conclusion [10] that "the shorter the reverberation time, the more important the earliest reflections are" is demonstrated in the results for Ross Uniting Church. Furthermore, they conclude that "after about 35 milliseconds of reflection delay the statistical reverberation completely dominates the singer's perception of the performance environment, irrespective of the presence of reflections." This is somewhat supported in our findings which indicate overall preference for low ST_{Early} and high RT.

The results also contrast against Marshall and Meyer's study showing early reflection amplitude having a greater influence on preference, compared with reverberation time [10]. This is not supported by our data which indicates that overall acoustic impressions are more influenced by reverberation time compared with sound strength parameters G and G_{Early}. It is possible that this inverse priority is due to the differences between a quartet singing one-per-part and a large choir, or a discrepancy in experience levels[8].

There was negligible evidence to show ST_{Early} correspond to "ensemble conditions" and ST_{Late} to "perceived reverberance" in accordance with ISO 3382-1:2009. The data weakly indicates that perceived support by the singers may be attributed to late reverberant energy. Highly rated venues for support generally have higher reverberation times and late sound strength G_{Late}, and lower levels in clarity metrics C_{80} and C_{50}.

High levels of lateral energy at Ross Uniting Church may also increase perceived reverberation and support, but evidence across venues with a range of J_{LF} is limited. Ross Uniting Church is a venue that would not typically be selected as a performance space for a 40+ person choir. It is an example of acoustic parameters that were on the more extreme end for choir performance spaces.

Higher bass ratio may enable a more "balanced" sound across the voice sections, particularly when there is less sound energy from the lower voice parts in the choir.

There is negligible statistical evidence that point to acoustic metrics which indicate singers' ability to hear themselves. It is likely that this is influenced by the SOR, which is highly dependent on singer spacing. As this metric could not be measured, and singer spacing varied between venues, further studies in more controlled environments are likely to provide more indicative results.

Figure 38: NZYC performing *Kua Rongo* at Ian Roach Hall, Scotch College (© Lucas Packett Photography 2022)

---

[8] Comment from H. Marshall: "Our sample was only a fraction of yours and none of them were 'professional.'"

5.3 Limitations and Future Work

5.3.1 Order of performance

Due to the nature of touring, results may be affected by the order in which the venues are performed in. However, most singers will have significant experience in performing at various venues and will have previous experience to draw from.

Physical fatigue may affect singers' vocal ability and mental capacity, and this may have affected responses when there were multiple performances in a day or on long travel days. Similarly, the time of day of the performance may also affect the singers' vocal ability.

5.3.2 Variation in response

Not all singers responded to the questionnaire at their earliest convenience following each performance. Some were submitted over a week after the performance, and the time delay may have affected singers' ability to recall their impressions.

Not all members of the choir were present at the Hobart and Melbourne concerts due to COVID infections, including those who were participating in the study. The choir's "sound" would not have been consistent for every concert, and this may affect singers' acoustic perception of the spaces.

The results may be weighted towards the opinions of singers' who were present at and submitted the most responses.

5.3.3 Variation in repertoire

The repertoire sung at each venue was generally chosen within a day of the performance, and were selected to suit the acoustics of the space. It's anticipated that this would generally highlight the positive acoustic aspects of the space as these would be more clearly demonstrated in the music. It is possible that if the performance repertoire was more consistent between the venues and covered a wide range of styles and tempos, stronger trends would be observed in the subjective responses.

5.3.4 Limitations with time and equipment

Due to the logistics of international touring, it was most practical to use an IRIS Mini measurement kit as it was highly portable, and minimised set-up and pack-down time. This allowed the measurement of most standard room acoustics parameters, but excluded measurement methodologies that could account for binaural effects and source directionality.

Ideally, the measurements should be undertaken with HATS for both the source and receiver. This could account for inter-aural effects between an individual singer's ears, and the directionality of the voice particularly at high frequencies. This would enable measurements of the IACC and ST_v metrics.

Impulse response measurements should ideally be taken when the choir is on stage in performance positions. This could account for the additional localised absorption provided by the physical presence of bodies.

It is likely that these improvements to the method would be most suitably undertaken with a choir at local venues over a number of days.

5.3.5 Other subjective metrics

It is likely that the questionnaire would have benefitted from an additional subjective metric "loudness of response." There is some indication that particularly high levels of G_{Early} may influence singers' perception of reverberance. It is also hypothesised that this would influence singers' ability to hear themselves, but this would likely require studies in a more controlled environment where singer spacing may be controlled.

5.3.6 Architectural considerations

The dimensions of the “stage” and “room” were not interrogated in this study. There is literature that discusses the influence of room dimensions for orchestras, but none for singers or vocal ensembles.

Furthermore, all neo-Gothic cathedral venues had chancels of varying dimensions. It’s noted that the chancel at St David’s Cathedral had a glazed partition separating the nave and transept from the chancel. Spaces with chancels would likely demonstrate effects of acoustically coupled spaces, including different reverberant and directional effects. Spaces without chancels typically have the back wall as the nearest vertical reflecting surface. However, there is little support in literature for rear reflectors for instrumentalists and singers.

5.3.7 Variation in individual auditory experience

For singers who provided questionnaire responses to the majority of the venues, it would be possible to identify individual trends in the responses. It may also be possible to identify trends depending on voice part.

A study by Daugherty et al. [44] with a SATB choir showed that most choristers perceived that horizontal singer spacing and riser step height influenced choral sound. Of the tour venues, risers of varying dimensions were used at TFC, IRH and SOH. In most of the church venues, there was some sort of raised platform for allow for some elevation of the singers, typically the back row(s). A raised conductor’s podium was also used by the music director in some venues.

The study did not account for these variations, as each individual singer’s position on stage was not recorded. However, most performances required singers to stand in a number of different positions across the stage and so each individual’s sample of positions is difficult to track and account for.

The Lombard effect and SOR was not able to be measured directly due to logistical limitations, however comments from the respondents on their vocal technique and effort provide us some context. The author considers that the Lombard effect was best demonstrated to the singers at RUC, and it is noted that many respondents made conscious efforts to reduce their vocal effort in response.

5.3.8 Bias in discussion

There is likely to be some inherent bias in the interpretation and discussion of the results due to the author being part of the choir in the study. The author has not participated in the questionnaire, or disclosed their opinion or data to the singers during the period of data collection.

The author has taken steps to anonymise subjective results from the questionnaire, and analyse the data scientifically from an acoustician’s perspective.

Ideally, the researcher should be a third party not associated with the choir, such as for the similar studies with touring instrumentalists. However, this would have presented logistical and financial challenges for this project.

5.3.9 Statistical modelling

There may be some potential to analyse the data or conduct further studies where the data is analysed using a linear mixed effect model. This method would be useful in introducing fixed effects such as voice part. These methods are not commonly used in the field of subjective acoustic studies, and further investigation would be required to test the applicability of the model.

Principal Component Analysis (PCA) may be used to validate the suitability of the subjective metrics in the questionnaire, and whether other metrics may be more appropriate for choral singers. However, a separate study in a more controlled environment may yield clearer results.

APPENDIX A GLOSSARY OF ACOUSTIC TERMINOLOGY

Frequency	Sound occurs over a range of frequencies, extending from the very low (e.g. thunder) to the very high (e.g. mosquito buzz). Measured in units of Hertz (Hz). Humans typically hear sounds between 20 Hz and 20 kHz. High frequency acuity naturally reduces with age most adults can hear up to 15 kHz.
Hertz (Hz)	The unit of frequency, named after Gustav Hertz (1887-1975). One hertz is one pressure cycle of sound per second. One thousand hertz – 1000 cycles per second – is a kilohertz (kHz).
Octave band	The interval between one frequency and its double. Sound is divided into octave bands for analysis. The typical octave band centre frequencies are 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz and 4 kHz.
Third octave band	One-third of an octave band. Used for more detailed analysis of sound frequency.
A-weighting	A set of frequency-dependent sound level adjustments that are used to better represent how humans hear sounds. Humans are less sensitive to low and very high frequency sounds. Sound levels using an "A" frequency weighting are expressed as dB L_A. Alternative ways of expressing A-weighted decibels are dBA or dB(A).
dB	Decibel. The unit of sound level.
Absorption coefficient	A measure of the proportion of sound energy absorbed by a material. It is represented by α. An α of 0 means it is fully reflective and an α of 1 means it is fully absorptive at the specified frequency.
Bass Rise	The ratio of $T_{(125Hz)}$ to $T_{(mid)}$. Bass rise characterises the sense of warmth to the sound quality.
C_{50}	Speech clarity. The logarithmic ratio of the early to late energy for the decay from an impulse based on a time interval of 50 ms, measured in decibels. A higher value of C_{50} corresponds to higher speech intelligibility.
C_{80}	Musical clarity. The logarithmic ratio of the early to late energy for the decay from an impulse based on a time interval of 80 ms, measured in decibels. C_{80} is a measure of the balance between hearing musical details and the reverberance. A higher value indicates that fine details of articulation and tone colour in a musical work can be more easily heard.
D_{50}	Definition. The ratio of the early to total energy for the decay from an impulse based on a time interval of 50 ms. A higher value of D50 corresponds to higher speech intelligibility.
EDT	Early Decay Time or Running Decay Time. The estimated reverberation time based on the measured decay from 0 to -10 decibels. EDT is correlated to the running reverberation, which is the reverberation heard within a musical phrase.
G	Source Strength or Loudness. A measure of the absolute loudness or "room gain" of an auditorium, used to describe how much the room itself "amplifies" a performance. G is defined as the logarithmic ratio of the sound level at a seat compared to the level at 10 m in a free field. The source is usually located at the stage area. A room with higher G has a higher sound level in forte and allows a wider dynamic range.

Impulse response	The sequence of sound reflections that arrives at a listening/measurement position after a sudden short sound (e.g. a hand clap) at the sound source location. The impulse response can be thought of as the "acoustic signature" of the room and will vary from room to room and from seat to seat within the room. The loudness, direction and timing of individual reflections within the impulse response determines the acoustic quality of the room. Most acoustic parameters are derived from analysis of the impulse response.
LF_{80}	Early Lateral Fraction. LF_{80} is the ratio of the early sound (within 80 ms) that arrives at the listener position from the sides. More early lateral sound energy increases the apparent width of the source and allows increased sense of spaciousness and involvement in the performance.
T or RT	Reverberation Time. The time measured in seconds for the sound level in a room to decay by 60 decibels. A longer value for T corresponds to a more acoustically lively space, resulting in more build-up of sound level and weaker clarity/intelligibility. T is well correlated to the terminal reverberation, the sense of hearing the entire room resound at the end of a phrase e.g. after a stop chord. T is commonly evaluated over a shorter decay range (see T_{20} and T_{30}) due to difficulties in achieving 60 decibel of signal-to-noise in larger or noisier rooms. Where not otherwise specified, T refers to the mid frequency value $T_{(mid)}$ – the average of the measured values for the 500 Hz and 1 kHz octave bands.
Scattering or Diffusion	The ability of a surface to redirect sound away from the specular (mirror image) direction. The correct amount of scattering/diffusion is beneficial in music auditoriums to increase the spatial coverage from a surface, to reduce the strength of excessively strong reflections without absorbing the sound energy (e.g. to suppress an echo) and to address harsh tone quality that can occur from large smooth surfaces. However, too much scattering is problematic and can make the room feel distant and unfocused. Strictly speaking, scattering refers to how much sound is sent away from the specular direction while diffusion refers to an even distribution of the scattered sound. However, the two terms are commonly used interchangeably.
ST_{early} or ST1	Early Stage Support. The logarithmic ratio of early reflected (20 – 100 ms) to direct (0 – 20 ms) energy measured at 1 m from the source. A higher value of ST_{early} correlates with the ease with which a musician on stage can hear their own sound.
ST_{late}	Late Stage Support. The logarithmic ratio of late reflected (100 – 1000 ms) to direct (0 – 20 ms) energy measured at 1 m from the source. A higher value of ST_{late} correlates with the ease with which a musician on stage can hear the reverberance in the hall.
T_{20}	The estimated reverberation time based on the measured decay between -5 and -25 decibels.
T_{30}	The estimated reverberation time based on the measured decay between -5 and -35 decibels.
T_{60}	The estimated reverberation time based on the measured decay between -5 and -65 decibels.

APPENDIX B REFERENCES

[1] A. C. Gade, ‘Investigations of musicians’ room acoustic conditions in concert halls. Part II: Field experiments and synthesis of results.’, *Acta Acustica united with Acustica*, vol. 69, no. 5, pp. 249–261, 1989.

[2] M. Barron, ‘Subjective Study of British Symphony Concert Halls’, *Acta Acustica united with Acustica*, vol. 66, no. 1, pp. 1–14, 1988.

[3] A. H. Marshall, D. Gottlob, and H. Alrutz, ‘The acoustical conditions preferred for ensemble’, *J Acoust Soc Am*, vol. 63, no. S1, pp. S35–S36, May 1978, doi: 10.1121/1.2016618.

[4] J. J. Dammerud, ‘Stage Acoustics for Symphony Orchestras in Concert Halls’, University of Bath, 2009. [Online]. Available: stageac.wordpress.com/phd/

[5] L. Panton, ‘Investigating Auditorium Acoustics from the Perspective of Musicians’, University of Tasmania, 2017. doi: 10.25959/23239754.v1.

[6] L. Panton, D. Holloway, D. Cabrera, and L. Miranda, ‘Stage Acoustics in Eight Australian Concert Halls: Acoustic Conditions in Relation to Subjective Assessments by a Touring Chamber Orchestra’, *Acoust Aust*, vol. 45, no. 1, pp. 25–39, Apr. 2017, doi: 10.1007/s40857-016-0075-2.

[7] R. C. J. van Luxemburg, C. C. J. M. Hak, P. H. Heijnen, and M. Kivits, ‘Stage acoustics: experiments on 7 stages of concert halls in the Netherlands’, in *Proceedings of Internoise Ottawa, Canada*, 2009.

[8] Y. Toyota, ‘Questionnaire survey on the subjective impression of stage acoustics of European concert halls through the Japanese Philharmonic Orchestra Tour’, *J Acoust Soc Am*, vol. 100, no. 4_Supplement, pp. 2837–2837, Oct. 1996, doi: 10.1121/1.416705.

[9] J. Sanders, ‘Suitability of New Zealand Halls for Chamber Music’, *New Zealand Acoustics*, vol. 15, no. 1, pp. 20–27, 2022, [Online]. Available: acoustics.org.nz/journal-articles

[10] A. H. Marshall and J. Meyer, ‘The directivity and auditory impressions of singers’, *Acta Acustica united with Acustica*, vol. 58, no. 3, pp. 130–140, 1985.

[11] E. van den Braak, H. Marshall, J. Meyer, M. Halstead, and D. Protheroe, ‘Further Investigation of Ensemble Singers Preferred Sound Fields’, in *Proceedings of the International Symposium on Room Acoustics*, Amsterdam, Sep. 2019, pp. 39–46. doi: 10.18154/RWTH-CONV-240098.

[12] A. Burd and L. Haslam, ‘The relationship of choir and orchestra in concert halls’, *Institute of Acoustics Proceedings*, vol. 16, no. 2, pp. 479–485, 1994, [Online]. Available: ioa.org.uk/catalogue/article/relationship-choir-and-orchestra-concert-halls

[13] T. Fischinger, K. Frieler, and J. Louhivuori, ‘Influence of virtual room acoustics on choir singing.’, *Psychomusicology: Music, Mind, and Brain*, vol. 25, no. 3, pp. 208–218, Sep. 2015, doi: 10.1037/pmu0000117.

[14] D. Bonsi, M. Longair, P. Garsed, and R. Orlowski, ‘Acoustic and audience response analyses of eleven Venetian churches’, *J Acoust Soc Am*, vol. 123, no. 5_Supplement, pp. 3353–3353, May 2008, doi: 10.1121/1.2933918.

[15] J. S. Brereton, ‘Singing in Space(s): Singing performance in real and virtual acoustic environments—Singers’ evaluation, performance analysis and listeners’ perception.’, University of York, 2014. [Online]. Available: pure.york.ac.uk/portal/en/publications/singing-in-spaces-singing-performance-in-real-and-virtual-acousti

[16] K. S. Hom, ‘The effect of two different rooms on acoustical and perceptual measures of SATB choir sound’, University of Kansas, 2013. [Online]. Available: hdl.handle.net/1808/12195

[17] S. Tonkinson, ‘The Lombard effect in choral singing’, *Journal of Voice*, vol. 8, no. 1, pp. 24–29, Mar. 1994, doi: 10.1016/S0892-1997(05)80316-9.

[18] S. Ternström, ‘Hearing myself with others: Sound levels in choral performance measured with separation of one’s own voice from the rest of the choir’, *Journal of Voice*, vol. 8, no. 4, pp. 293–302, Dec. 1994, doi: 10.1016/S0892-1997(05)80277-2.

[19] S. Ternström, ‘Preferred self-to-other ratios in choir singing’, *J Acoust Soc Am*, vol. 105, no. 6, pp. 3563–3574, Jun. 1999, doi: 10.1121/1.424680.

[20] P. Luizard, J. Steffens, and S. Weinzierl, ‘Singing in different rooms: Common or individual adaptation patterns to the acoustic conditions?’, *J Acoust Soc Am*, vol. 147, no. 2, pp. EL132–EL137, Feb. 2020, doi: 10.1121/10.0000715.

[21] Y. G. Redman, J. D. Glasner, D. D’Orazio, and P. Bottalico, ‘Singing in different performance spaces: The effect of room acoustics on singers’ perception’, *J Acoust Soc Am*, vol. 154, no. 4, pp. 2256–2264, Oct. 2023, doi: 10.1121/10.0021331.

[22] S. Ternström, ‘Long-time average spectrum characteristics of different choirs in different rooms’, *Voice*, vol. 2, pp. 55–77, Aug. 1993.

[23] P. Luizard, E. Brauer, S. Weinzierl, and N. Henrich Bernardoni, ‘How singers adapt to room acoustical conditions’, *Proceedings of the Institute of Acoustics*, vol. 40, no. 3, 2018.

[24] K. Adams, ‘Choral Configuration: An Overview of Research and Implications for the Choral Music Educator’, *Update: Applications of Research in Music Education*, vol. 37, no. 2, pp. 24–29, Feb. 2019, doi: 10.1177/8755123318783526.

[25] V. L. Jordan, *Acoustical Design of Concert Halls and Theatres*. Applied Science Publishers, 1980.

[26] ScotchArts 2014, ‘ScotchArts 2014 Season > Ian Roach Hall’. [Online]. Available: scotch.vic.edu.au/scotcharts/irh.htm

[27] G. Engel and J. Reinhold, ‘Acoustic upgrade for the Concert Hall of the Sydney Opera House’, *Proceedings of the Institute of Acoustics*, vol. 45, no. 2, 2023.

[28] L. Panton, D. Holloway, and D. Cabrera, ‘Investigating concern hall acoustics from musicians’ perspective: summary of results from a survey of two touring chamber orchestras’, in *Acoustics 2015 Hunter Valley*, Aug. 2015.

[29] A. C. Gade, ‘Investigations of Musicians’ Room Acoustic Conditions in Concert Halls. Part I: Methods and Laboratory Experiments’, *Acta Acustica united with Acustica*, vol. 69, no. 5, pp. 193–203, 1989.

[30] L. A. Miranda Jofre, D. Cabrera, M. Yadav, A. Sygulska, and W. Martens, ‘Evaluation of stage acoustics preference for a singer using oral-binaural room impulse responses’, *Proceedings of Meetings on Acoustics*, vol. 19, no. 015074, Jun. 2013, doi: 10.1121/1.4800204.

[31] D. Pelegrín-García, ‘Comment on “Increase in voice level and speaker comfort in lecture rooms” [J. Acoust. Soc. Am. 125, 2072–2082 (2009)] (L)’, *J Acoust Soc Am*, vol. 129, no. 3, pp. 1161–1164, Mar. 2011, doi: 10.1121/1.3543940.

[32] J. Brunskog, A. C. Gade, G. P. Bellester, and L. R. Calbo, ‘Increase in voice level and speaker comfort in lecture rooms’, *J Acoust Soc Am*, vol. 125, no. 4, pp. 2072–2082, Apr. 2009, doi: 10.1121/1.3081396.

[33] A. C. Gade, ‘Practical aspects of room acoustic measurements on orchestra platforms’, in *Proceedings of 14th ICA*, Beijing, 1992.

[34] L. L. Beranek, *Music, acoustics & architecture*. New York: John Wiley & Sons, 1962.

[35] L. L. Beranek, ‘Subjective rank-orderings and acoustical measurements for fifty-eight concert halls’, *Acta Acustica united with Acustica*, vol. 89, no. 3, pp. 494–508, 2003.

[36] D. Noson, S. Sato, H. Sakai, and Y. Ando, ‘Singer responses to sound fields with a simulated reflection’, *J Sound Vib*, vol. 232, no. 1, pp. 39–51, Apr. 2000, doi: 10.1006/jsvi.1999.2684.

[37] International Organization for Standardization, ‘Acoustics —

Measurement of room acoustic parameters — Part 1: Performance spaces', Geneva, Switzerland, ISO 3382-1:2009, Jun. 2009.

[38] M. Dunn, '3D room acoustic measurements with low cost equipment', in *The Sound of a Changing World*, Auckland: Acoustical Society of New Zealand, Jun. 2021.

[39] Y. H. Kim, J. Y. Jeon, and D. Cabrera, 'Evaluation of stage support for musicians' performance in a concert hall ', in *Proceedings of 20th International Congress on Acoustics, ICA 2010*, Sydney, Aug. 2010.

[40] C. M. Harris, *Handbook of Noise Control*. McGraw Hill, 1997.

[41] M. D. Egan, *Architectural Acoustics*. McGraw-Hill, 1988.

[42] J. O. Utzon, 'Sydney National Opera House ("Red Book")', 1958. [Online]. Available: search.records.nsw.gov.au/permalink/f/1ebnd1l/ADLIB_RNSW112412871

[43] V. L. Jordan, 'Acoustical Design Considerations of the Sydney Opera House', *Journal and Proceedings of The Royal Society of New South Wales*, vol. 106, no. 1 & 2, pp. 33–53, Nov. 1973.

[44] J. F. Daugherty, J. N. Manternach, and M. C. Brunkan, 'Acoustic and perceptual measures of SATB choir performances on two types of portable choral riser units in three singer-spacing conditions', *International Journal of Music Education*, vol. 31, no. 3, pp. 359–375, Aug. 2013, doi: 10.1177/0255761411434499.

APPENDIX C LIST OF REPERTOIRE

Repertoire for the performances at each venue were selected from the list in Table 12. These were generally selected by the music director to suit the acoustical and cultural aspects of the venue.

Table 12: List of NZYC Australian Tour 2022 repertoire

Title of piece	Composer	Voicing
There is Sweet Music	Edward Elgar	SSAATTBB
Hymn to St Cecilia	Benjamin Britten	SSATB + solos
Elijah Rock	Trad. Spiritual, arr. Hogan	SSSAATTBB
Suite de Lorca	Einojuhani Rautavaara	SATB div + solos
Zwei Motetten, Op.29, No.1	Johannes Brahms	SATB div
Duo Seraphim a 12	Francisco Guerrero	3x 4-part choirs
Love is here to stay	Gershwin, arr. Meader	SATB div
Steal Away	arr. Diedre Robinson	SATB div
Ecce Concipies	Mark Sirett	SATB
The Drunken Sailor	arr. Robert Sund	SATB div
Matariki: Ngā whetu piataata	Chris Artley	SATB div
Kua Rongo	Te Whanau Wehi	SATB div + guitar
Takoto mai ra	Reuben Rameka	STB div + solos
Lux Aurumque	Eric Whitacre	SATB div + solo
Sunday	Stephen Sondheim, arr. Huff	SATB + piano
Ka Waiata Ki a Maria	Richard Puanaki	SATB div
Oculi Omnium	Charles Wood	SATB
A Boy and a Girl	Eric Whitacre	SATB div
The City and the Sea (x5 songs)	Eric Whitacre	SATB + piano
Forest Song	Rosa Elliott	SSSAAATTTBBB
O Nata Lux	David Hamilton	SATB div
Ko ngā waka ēnei	Trad.	A cappella
Tutira mai ngā iwi	Wi Te Tau Huata	SATB div + guitar
Silent Night / Po Marie	Gruber, arr. Maskell	SAATB div
Angels from the Realms of Glory	arr. Walker	SAB + piano
Deck the Halls with Holly Ivy	arr. Elsley	SATB div, piano, flute
Sacred Stepping Stones	Lisa Young	SSAATB + drum

APPENDIX D SINGER RESPONSE QUESTIONNAIRE

The singer response questionnaire was provided to the singers on the day of first performance of the tour.

D1 Paper/PDF Questionnaire

Thank you for signing up to participate in this study. Your response is valuable in furthering the understanding of how singers respond to acoustic spaces.

Project Background

The New Zealand Youth Choir (NZYC) is touring Australia on 27 November to 15 December 2022. During this time, the choir will be performing in a range of venues ranging from large concerts halls to smaller performance spaces such as theatres, traditional churches, and recital halls.

The tour has been identified as an opportunity to conduct a research project on the acoustic stage response of singers and conductors. As the tour inherently involves a fixed group of singers performing at various venues within a short period of time, it provides the opportunity for direct subjective comparisons by the group.

Aims and Desired Outcomes

This project aims to bridge the understanding of singers' subjective acoustic response with objective acoustic parameters. The results of the study may be used to inform architectural considerations when designing or retrofitting a performance venue to support unamplified vocal ensembles.

Those who would be interested in the outcomes of the study would fall into two broad categories: musicians and designers. Musicians would include singers themselves, conductors and directors, and by extension ensemble managers when resourcing venues. Designers would include acousticians, architects, and interior designers.

Instructions

It is optional to fill in your name, only your voice part (e.g., Soprano 1, Tenor 2) is required. Your name will only be used to follow-up your responses to clarify your comments. All names will be kept anonymous in any discussion and presentation of results.

Please fill in one questionnaire sheet for each performance venue. Aim to fill in the questionnaire prior to singing in the next venue, so your responses are not influenced by another venue.

Please fill in each question as best as you can, and keep in mind that it is from the perspective of a singer on stage and not the audience. You do not need to use "acoustic" or "scientific" language, I am looking for intuitive and natural responses. Please feel free to ask for clarifications on any questions that you are not sure of.

The questionnaire should be filled out individually. You are welcome to discuss your impressions of the space with other singers and staff. However, please avoid discussing your response to the questionnaire to avoid influencing other singers' answers. Please feel free to disagree with any opinions that others may have presented, even if it's the opinions of music staff.

There will be an opportunity to review your responses at the end of the tour. If you need to make any changes to your responses, please make a note on the questionnaire for the reasons of change.

Access a digital version of the form at this link: https://forms.gle/SZE8VTjeJn5xFjtJ6 or scan the QR code to the right.

SINGER RESPONSE QUESTIONNAIRE

Name (optional)**:**	**Venue:**
Voice part:	**Performance Date:**

Singing Experience

Overall Acoustic Impression	Very unsatisfying performance experience	0 1 2 3 4 5 6 7 8 9 10	Very rewarding performance experience
Hearing Self	Difficult to hear own voice	0 1 2 3 4 5 6 7 8 9 10	Easy to hear own voice
Support	Feeling of singing alone	0 1 2 3 4 5 6 7 8 9 10	Sound well supported, easy to project
Ensemble (e.g., keeping tempo and pitch with others)	Difficult to hear other voices	0 1 2 3 4 5 6 7 8 9 10	Easy to hear other voices

Were there any voice part(s) that was **more difficult to hear** in the venue? ______________________________

Were there any voice part(s) that you could **hear particularly prominently** in the venue? ____________________

Did you (or feel the need to) alter your typical singing technique to adapt to the venue? If yes, how? ____________
____

Any additional comments on the singing experience, audibility and balance of sounds/voices within the venue?

In your opinion: Which piece(s) **best** suited the venue? ______________________________

Which piece(s) **least** suited the venue? ______________________________

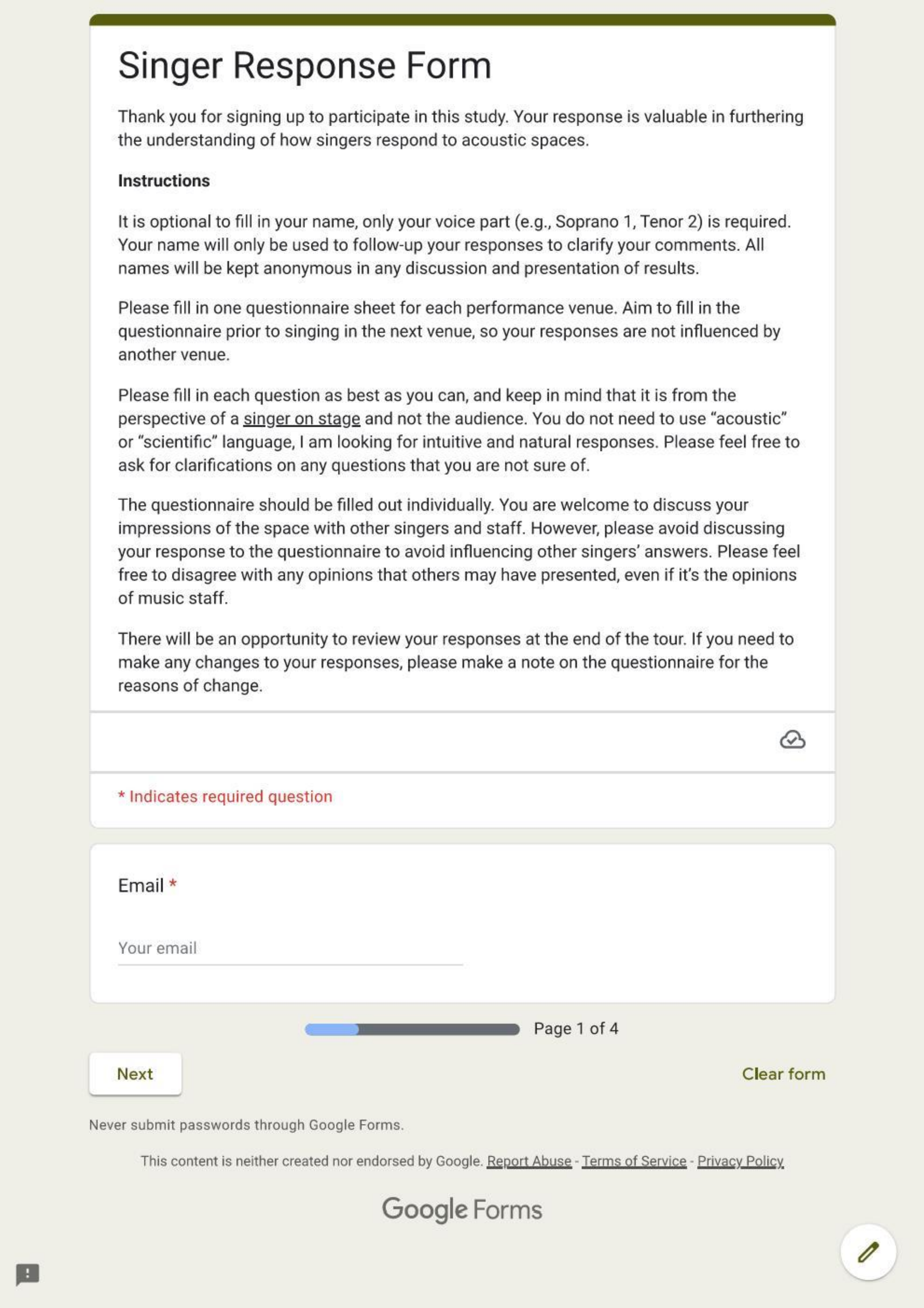
Auditory and Visual Experience

Reverberance	Dry	Live 0 1 2 3 4 5 6 7 8 9 10	Overly Reverberant
Clarity (e.g., of consonants)	Muddy	0 1 2 3 4 5 6 7 8 9 10	Clear
Timbre	Brilliant and bright	0 1 2 3 4 5 6 7 8 9 10	Warm and mellow
Dynamic Range	Difficult to achieve variation in dynamics	0 1 2 3 4 5 6 7 8 9 10	Easy to achieve *fortissimo* and *pianissimo*
Visual Impression	Unsightly/repellent	0 1 2 3 4 5 6 7 8 9 10	Gratifying

Did you hear any distracting/unexpected echoes? If yes, from what general direction? ____________________

Any other general comments?

D2 Online Google Form Questionnaire



Singer Response Form

Thank you for signing up to participate in this study. Your response is valuable in furthering the understanding of how singers respond to acoustic spaces.

Instructions

It is optional to fill in your name, only your voice part (e.g., Soprano 1, Tenor 2) is required. Your name will only be used to follow-up your responses to clarify your comments. All names will be kept anonymous in any discussion and presentation of results.

Please fill in one questionnaire sheet for each performance venue. Aim to fill in the questionnaire prior to singing in the next venue, so your responses are not influenced by another venue.

Please fill in each question as best as you can, and keep in mind that it is from the perspective of a singer on stage and not the audience. You do not need to use “acoustic” or “scientific” language, I am looking for intuitive and natural responses. Please feel free to ask for clarifications on any questions that you are not sure of.

The questionnaire should be filled out individually. You are welcome to discuss your impressions of the space with other singers and staff. However, please avoid discussing your response to the questionnaire to avoid influencing other singers’ answers. Please feel free to disagree with any opinions that others may have presented, even if it’s the opinions of music staff.

There will be an opportunity to review your responses at the end of the tour. If you need to make any changes to your responses, please make a note on the questionnaire for the reasons of change.

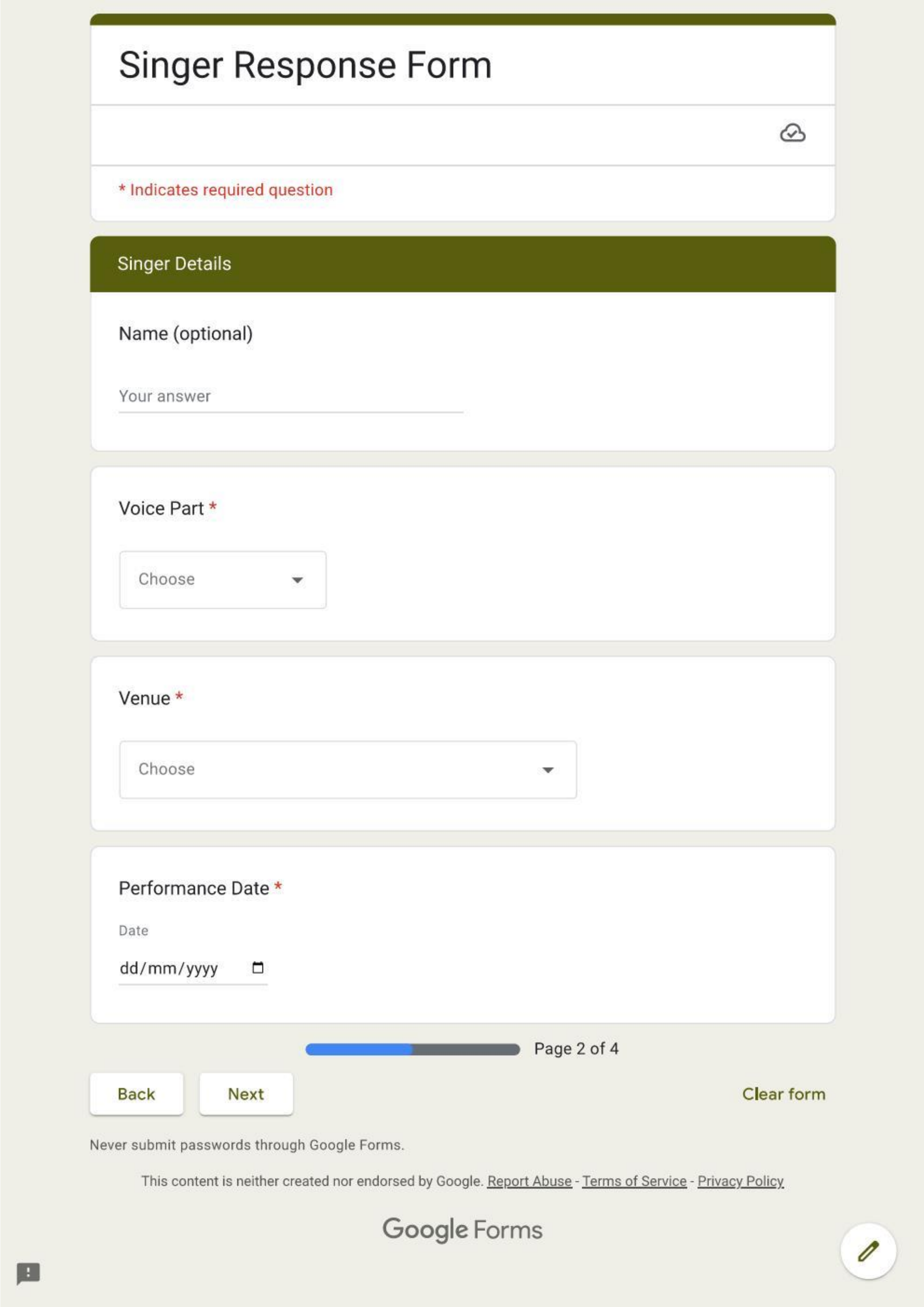
* Indicates required question

Email *

Your email

Never submit passwords through Google Forms.

This content is neither created nor endorsed by Google. Report Abuse - Terms of Service - Privacy Policy



Singer Response Form

* Indicates required question

Singer Details

Name (optional)

Your answer

Voice Part *

Choose

Venue *

Choose

Performance Date *

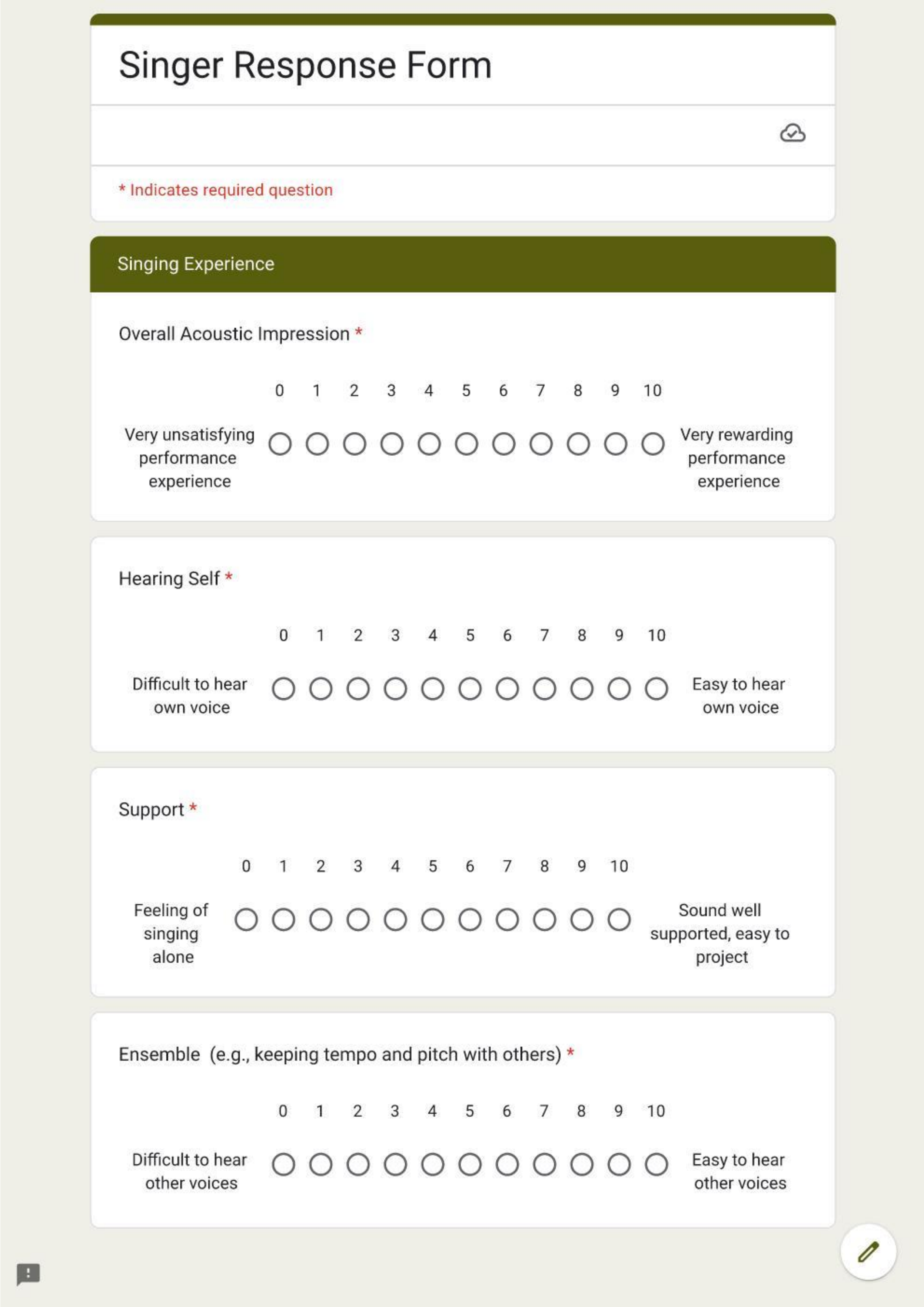
Date

dd/mm/yyyy

Page 2 of 4

Never submit passwords through Google Forms.

This content is neither created nor endorsed by Google. Report Abuse - Terms of Service - Privacy Policy



Singer Response Form

* Indicates required question

Singing Experience

Overall Acoustic Impression *

	0	1	2	3	4	5	6	7	8	9	10	
Very unsatisfying performance experience	○	○	○	○	○	○	○	○	○	○	○	Very rewarding performance experience

Hearing Self *

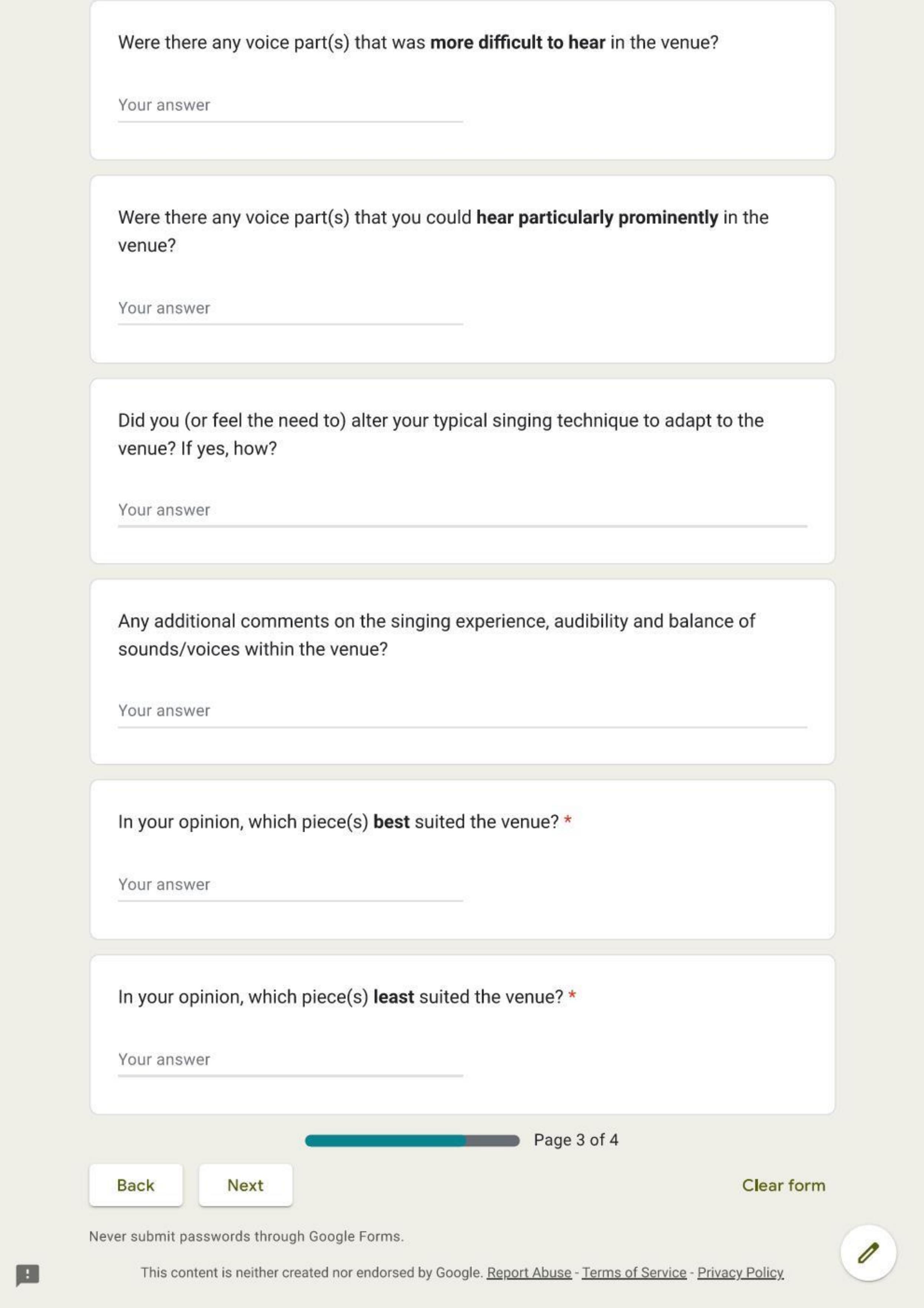
	0	1	2	3	4	5	6	7	8	9	10	
Difficult to hear own voice	○	○	○	○	○	○	○	○	○	○	○	Easy to hear own voice

Support *

	0	1	2	3	4	5	6	7	8	9	10	
Feeling of singing alone	○	○	○	○	○	○	○	○	○	○	○	Sound well supported, easy to project

Ensemble (e.g., keeping tempo and pitch with others) *

	0	1	2	3	4	5	6	7	8	9	10	
Difficult to hear other voices	○	○	○	○	○	○	○	○	○	○	○	Easy to hear other voices



Were there any voice part(s) that was **more difficult to hear** in the venue?

Your answer

Were there any voice part(s) that you could **hear particularly prominently** in the venue?

Your answer

Did you (or feel the need to) alter your typical singing technique to adapt to the venue? If yes, how?

Your answer

Any additional comments on the singing experience, audibility and balance of sounds/voices within the venue?

Your answer

In your opinion, which piece(s) **best** suited the venue? *

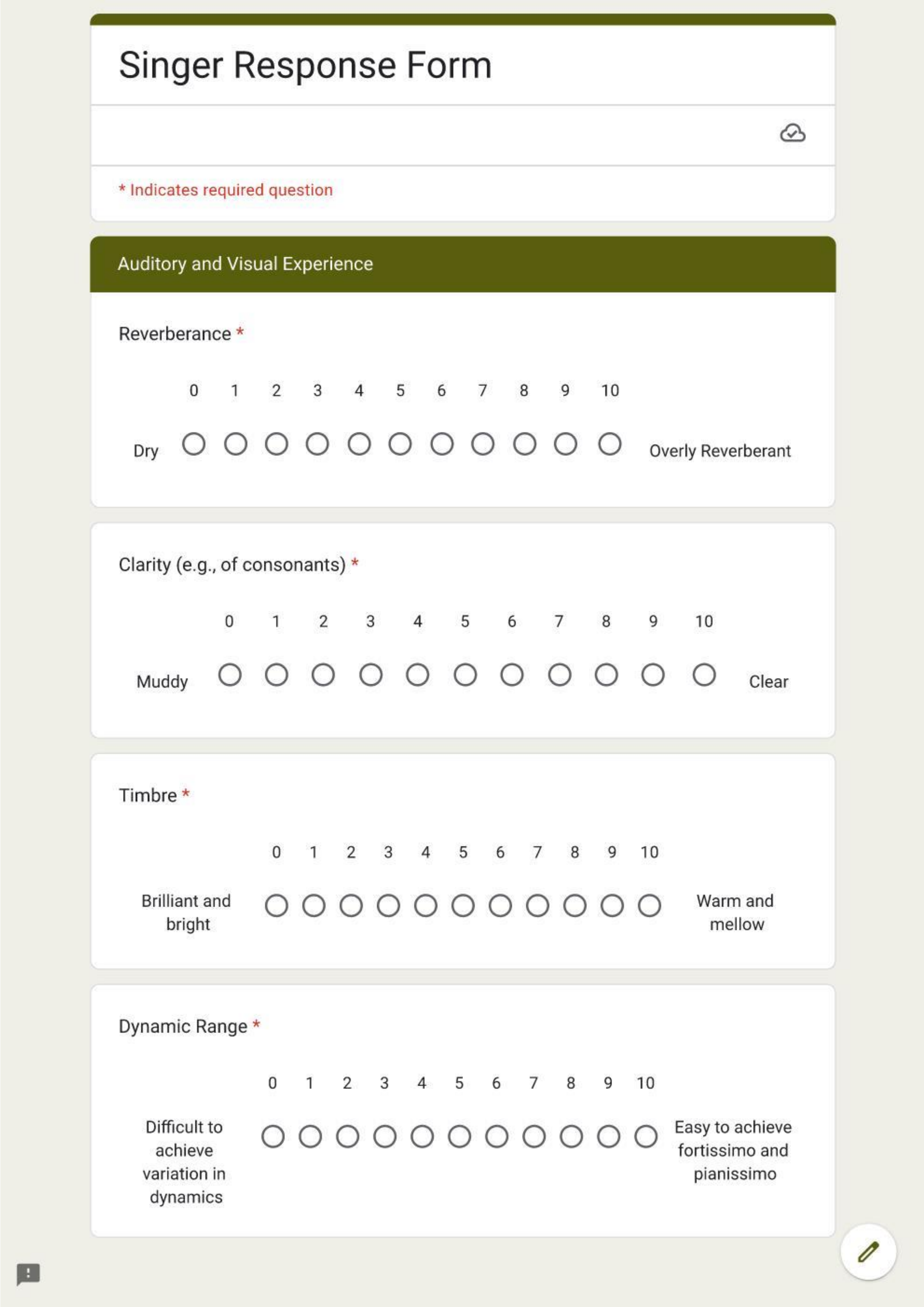
Your answer

In your opinion, which piece(s) **least** suited the venue? *

Your answer

Never submit passwords through Google Forms.

This content is neither created nor endorsed by Google. Report Abuse - Terms of Service - Privacy Policy



Singer Response Form

* Indicates required question

Auditory and Visual Experience

Reverberance *

	0	1	2	3	4	5	6	7	8	9	10	
Dry	○	○	○	○	○	○	○	○	○	○	○	Overly Reverberant

Clarity (e.g., of consonants) *

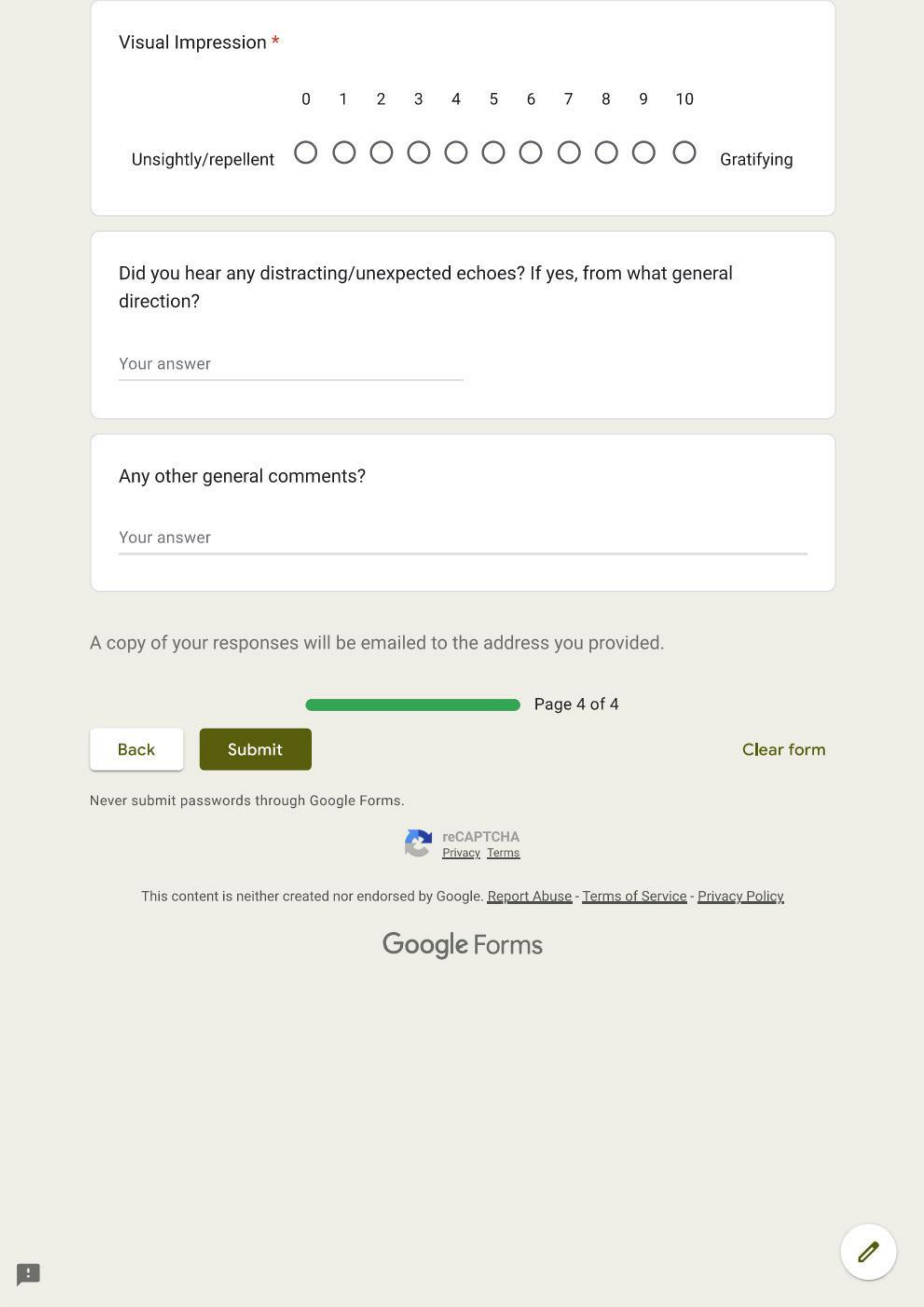
	0	1	2	3	4	5	6	7	8	9	10	
Muddy	○	○	○	○	○	○	○	○	○	○	○	Clear

Timbre *

	0	1	2	3	4	5	6	7	8	9	10	
Brilliant and bright	○	○	○	○	○	○	○	○	○	○	○	Warm and mellow

Dynamic Range *

	0	1	2	3	4	5	6	7	8	9	10	
Difficult to achieve variation in dynamics	○	○	○	○	○	○	○	○	○	○	○	Easy to achieve fortissimo and pianissimo



Visual Impression *

	0	1	2	3	4	5	6	7	8	9	10	
Unsightly/repellent	○	○	○	○	○	○	○	○	○	○	○	Gratifying

Did you hear any distracting/unexpected echoes? If yes, from what general direction?

Your answer

Any other general comments?

Your answer

A copy of your responses will be emailed to the address you provided.

Page 4 of 4

Never submit passwords through Google Forms.

This content is neither created nor endorsed by Google. Report Abuse - Terms of Service - Privacy Policy

APPENDIX E ACOUSTIC MEASUREMENT DATA

This appendix contains averaged acoustic measurements in each venue.

Sound strength calibration was not conducted for the specific kit used, so sound strength metrics G, G_{Early} and G_{Late} should be treated as relative only.

Calculated bass ratio (BR) and treble ratio (TR) are based on T_{30} values only.

E1 St Matthew-in-the-City

Table 13: SMC averaged acoustic measurements

Parameter (unit)		**Octave-band centre Frequency (Hz)**							
	Mid	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
1m measurements (positions A1, A2, B1, B2, C1, C2)									
T_{20} (s)	2.36	2.35	2.25	2.18	2.38	2.35	2.00	1.42	0.99
T_{30} (s)	2.58 *	2.33	2.50	2.38 *	2.66	2.58	2.22	1.71	1.19
ST_{Early} (dB)	–13.1	0.5 †	–6.6	–13.1	–13.1	–12.2	–13.5	–12.0	–13.3
ST_{Late} (dB)	–12.3	–5.0	–5.1	–11.8	–12.3	–11.5	–13.3	–14.5	–17.4
C_{80} (dB)	11.8	11.6	11.3	11.6	12.3	11.3	13.1	14.9	16.9
C_{50} (dB)	10.9	9.6	10.6	10.6	11.3	10.4	12.1	13.7	10.9
G (dB)	19.8	22.3	24.0	21.1	20.2	19.5	20.5	21.4	20.0
G_{Early} (dB)	19.5	22.1	23.7	20.7	20.2	18.9	20.3	21.2	19.9
G_{Late} (dB)	7.7	10.7	12.6	9.1	7.8	7.5	7.1	5.9	3.1
LF	0.07	0.24	0.15	0.04	0.03	0.04	0.03	0.05	0.28
BR	0.93								
TR	0.75								
* Measurements A1 (4.39 s) and C1 (4.42 s) 250 Hz reverberation time excluded from T_{30} average due to very high values measured, which were not observed in T_{20}. † Measurement C2 63 Hz early stage support excluded from octave band average due to very high value (10.3 dB).									
Cross-stage measurements (A3, B3)									
EDT (s)	2.28	1.53	2.00	1.86	2.25	2.32	1.98	1.38	0.92
T_{20} (s)	2.69	2.13	2.55	2.42	2.69	2.68	2.35	1.77	1.29
T_{30} (s)	2.68	1.99	2.55	2.54	2.71	2.66	2.40	1.84	1.38
C_{80} (dB)	1.4	–0.3	–2.4	1.5	1.4	1.4	1.8	4.8	8.1
C_{50} (dB)	–0.1	–1.6	–4.2	–0.3	–0.3	0.1	0.5	3.3	6.5
G (dB)	10.5	12.7	12.6	12.6	10.9	10.1	10.2	10.5	10.2
G_{80} (dB)	8.2	10.1	8.4	10.6	8.5	7.9	8.0	9.3	9.6
G_{Late} (dB)	6.7	9.8	10.5	8.4	7.0	6.4	6.1	4.3	0.9
BR	0.95								

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
TR	0.79								
Conductor’s position measurement (D1)									
EDT (s)	2.14	1.68	2.59	1.82	2.14	2.14	1.98	1.58	1.11
T_{20} (s)	2.58	2.32	2.67	2.52	2.55	2.61	2.34	1.82	1.26
T_{30} (s)	2.67	–	2.78	2.54	2.67	2.67	2.43	1.87	1.37
C_{80} (dB)	–0.1	0.5	–2.1	0.7	–0.6	0.5	0.5	3.3	7.5
C_{50} (dB)	–1.6	–0.5	–2.8	–1.0	–2.1	–1.1	–1.3	1.8	5.9
G (dB)	10.1	11.7	10.9	11.1	10.1	10.1	9.6	8.7	8.4
G_{80} (dB)	7.1	9.1	6.7	8.4	6.7	7.6	6.7	7.0	7.7
G_{Late} (dB)	7.2	8.6	8.8	7.7	7.4	7.0	6.1	3.7	0.2
LF	0.15	0.43	0.31	0.11	0.08	0.09	0.16	0.21	0.85
BR	1.00								
TR	0.80								

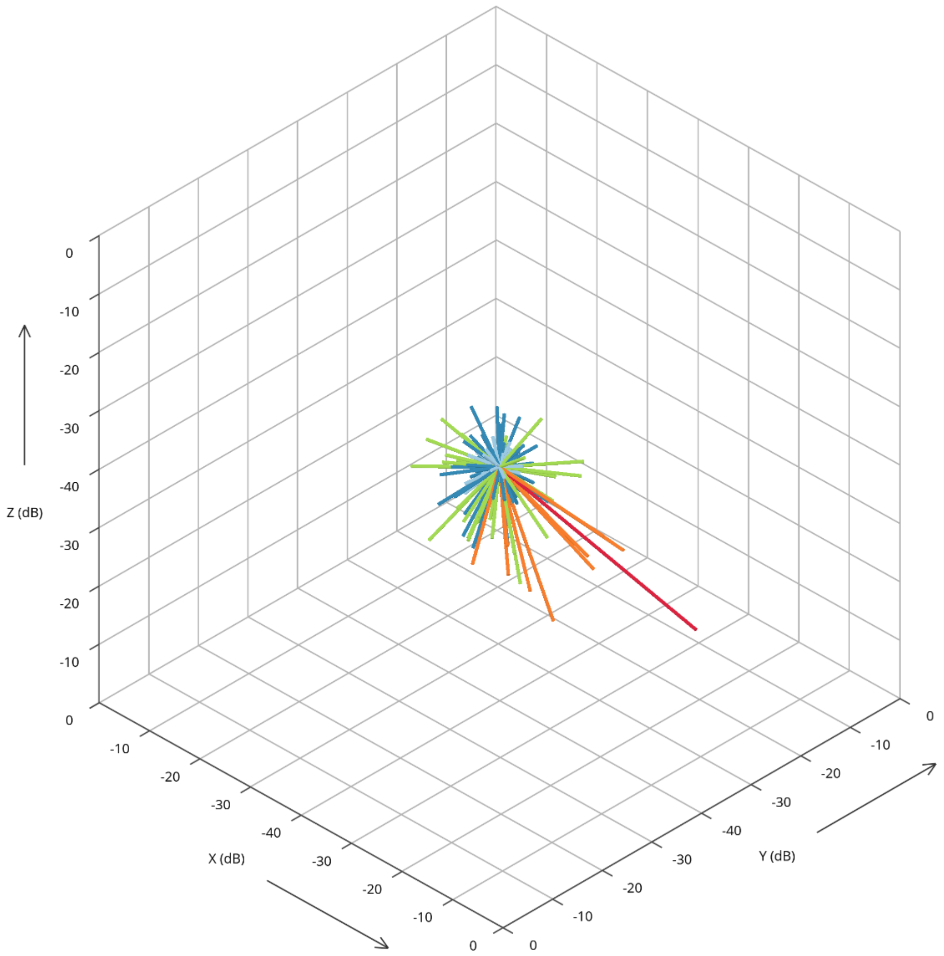


Figure 39: SMC measurement B1 IRIS 3-D sound intensity vector plot

E2 The Farrall Centre, The Friends' School

Table 14: TFC averaged acoustic measurements

Parameter (unit)		**Octave-band centre Frequency (Hz)**							
	Mid	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
1m measurements (positions A1, A2, B1, B2, C1) – measurement C2 failed to save									
T_{20} (s)	1.35	1.72	1.64	1.59	1.36	1.33	1.20	1.00	0.76
T_{30} (s)	1.38	1.63	1.81	1.69	1.39	1.37	1.25	1.06	0.80
ST_{Early} (dB)	–10.7	1.6	–2.5	–10.5	–10.4	–10.4	–11.1	–11.0	–12.7
ST_{Late} (dB)	–12.2	–8.8	–5.7	–11.3	–12.0	–12.6	–13.9	–14.6	–
C_{80} (dB)	12.8	9.6	11.7	12.0	12.6	13.0	13.9	15.6	19.0
C_{50} (dB)	11.3	7.5	10.3	10.6	11.1	11.4	12.4	13.8	16.6
G (dB)	19.2	21.9	22.9	20.0	19.4	19.0	19.7	19.4	19.7
G_{80} (dB)	19.0	21.6	22.6	19.8	19.1	18.9	19.4	19.3	19.7
G_{Late} (dB)	6.3	12.0	11.0	7.7	6.5	6.1	5.5	3.6	0.7
LF	0.05	0.11	0.08	0.05	0.03	0.04	0.05	0.06	0.46
BR	1.27								
TR	0.83								
Cross-stage measurements (A3, B3)									
EDT (s)	1.50	1.20	1.56	1.69	1.47	1.54	1.55	1.07	0.64
T_{20} (s)	1.38	1.26	1.85	1.67	1.40	1.37	1.26	1.06	0.85
T_{30} (s)	1.39	–	1.74	1.64	1.39	1.38	1.28	1.06	0.86
C_{80} (dB)	3.1	11.6	11.0	7.1	5.8	5.8	4.7	3.1	–0.2
C_{50} (dB)	1.6	0.4	0.4	0.5	0.4	0.3	0.2	0.3	1.2
G (dB)	10.8	16.6	14.9	10.9	11.1	10.4	10.8	11.1	11.4
G_{80} (dB)	9.1	15.3	12.5	8.7	9.6	8.7	9.6	10.3	11.1
G_{Late} (dB)	5.8	11.6	11.0	7.1	5.8	5.8	4.7	3.1	–0.2
BR	1.22								
TR	0.84								
Conductor's position measurement (D1) – measurement D1 failed to save									

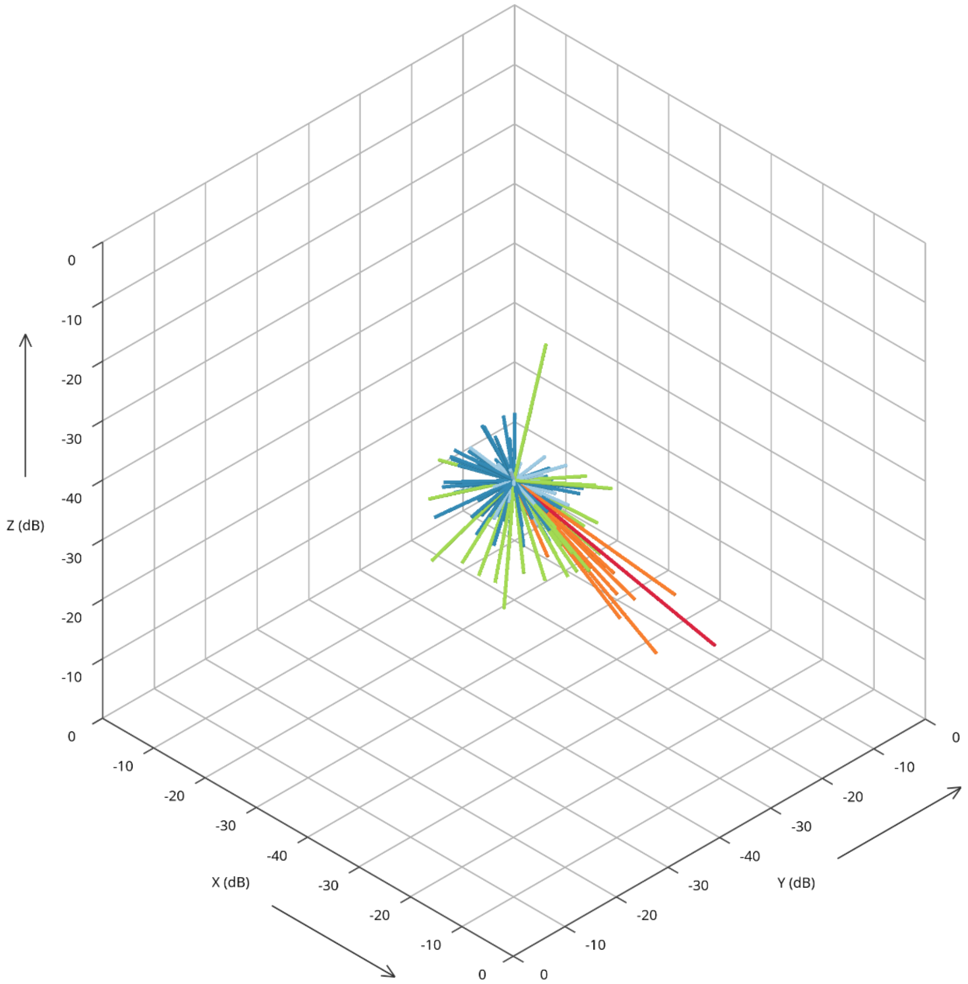


Figure 40: TFC measurement B1 IRIS 3-D sound intensity vector plot

E3 St David’s Cathedral

Table 15: SDC averaged acoustic measurements

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	63	125	250	500	1000	2000	4000	8000
1m measurements (positions A1, A2, B1, B2, C1, C2)									
T_{20} (s)	1.72	1.14	1.02	1.42	1.69	1.74	1.54	1.09	0.73
T_{30} (s)	1.91	1.14	1.23	1.68	1.93	1.90	1.72	1.30	0.86
ST_{Early} (dB)	–13.0	4.5	–5.5	–12.8	–12.6	–13.0	–13.4	–14.1	–13.1
ST_{Late} (dB)	–12.8	–	–	–13.7	–13.1	–12.4	–13.6	–17.3	–
C_{80} (dB)	12.6	12.6	15.2	14.3	13.1	12.2	13.2	16.8	18.1
C_{50} (dB)	11.7	9.3	14.0	13.2	12.2	11.3	12.1	15.4	15.9
G (dB)	20.7	23.6	24.3	21.6	20.9	20.4	20.9	22.6	20.4
G_{80} (dB)	20.4	23.5	24.2	21.4	20.7	20.1	20.7	22.5	20.4
G_{Late} (dB)	7.8	11.9	9.3	7.2	7.6	7.9	7.5	5.7	2.3
LF	0.06	0.54	0.12	0.04	0.04	0.03	0.03	0.02	0.36
BR	0.76								
TR	0.79								
Cross-stage measurements (A3, B3)									
EDT (s)	1.53	1.03	1.35	1.25	1.54	1.53	1.54	1.12	0.68
T_{20} (s)	1.93	1.51	1.46	1.50	1.89	1.97	1.83	1.39	0.93
T_{30} (s)	1.98	–	1.52	1.59	1.94	2.02	1.91	1.45	1.00
C_{80} (dB)	2.6	6.4	1.4	4.6	3.2	2.0	2.8	6.1	9.1
C_{50} (dB)	1.4	4.9	–0.1	3.6	2.3	0.6	1.2	4.2	6.7
G (dB)	12.1	14.0	11.7	12.7	12.7	11.5	11.0	11.5	10.6
G_{80} (dB)	10.2	13.4	9.4	11.6	10.9	9.5	9.2	10.6	10.2
G_{Late} (dB)	7.4	6.9	7.8	7.3	7.5	7.3	6.3	4.5	0.9
BR	0.78								
TR	0.85								
Conductor’s position measurement (D1)									
EDT (s)	1.97	0.82	1.27	1.36	2.18	1.76	1.63	1.33	0.83
T_{20} (s)	2.00	1.05	1.84	1.65	2.00	2.00	1.91	1.46	0.99
T_{30} (s)	2.01	–	–	1.68	1.95	2.07	1.89	1.49	1.05
C_{80} (dB)	0.4	7.0	2.7	3.0	–0.3	1.1	2.6	4.5	9.2
C_{50} (dB)	–0.8	6.2	–0.4	2.1	–1.4	–0.3	0.9	2.7	7.1

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
G (dB)	9.2	13.5	10.2	12.1	8.8	9.5	9.8	9.4	9.3
G_{80} (dB)	5.6	12.7	8.4	10.2	4.3	6.9	7.8	8.1	8.8
G_{Late} (dB)	5.2	5.8	5.7	7.2	4.6	5.7	5.2	3.5	–0.4
LF	0.29	0.29	0.26	0.11	0.57	0.21	0.12	0.17	0.79
BR *	0.87								
TR	0.84								

* BR calculated based on T_{20} 125 Hz value where T_{30} value not available.

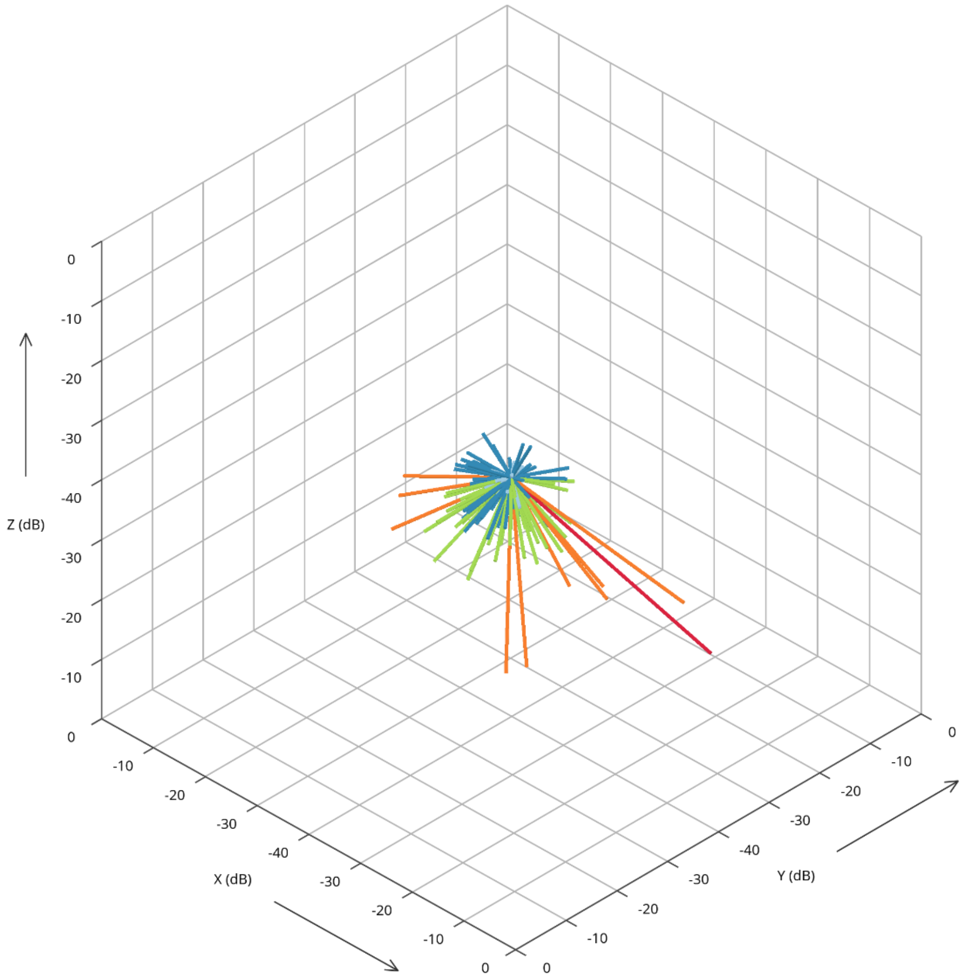


Figure 41: SDC measurement B1 IRIS 3-D sound intensity vector plot

E4 Ross Uniting Church

Table 16: RUC averaged acoustic measurements

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	63	125	250	500	1000	2000	4000	8000
1m measurements (positions A1, A2, B1, B2) – small stage geometry didn't allow for measurements in position C									
T_{20} (s)	1.55	1.17	1.11 *	1.08	1.46	1.64	1.45	1.18	0.83
T_{30} (s)	1.60	1.26	1.48 *	1.23	1.52	1.67	1.50	1.24	0.90
ST_{Early} (dB)	–6.1	2.8	–1.6	–5.8	–6.2	–6.2	–6.2	–5.7	–5.8
ST_{Late} (dB)	–7.8	–	–5.6	–8.3	–8.1	–7.0	–7.4	–8.9	–
C_{80} (dB)	8.0	5.1	10.1	9.5	8.5	7.4	8.2	9.2	11.8
C_{50} (dB)	6.1	0.2	7.9	6.7	6.5	5.7	6.5	7.0	9.1
G (dB)	21.0	22.9	23.4	21.8	21.3	20.7	20.9	20.8	20.3
G_{80} (dB)	20.4	22.3	22.9	21.4	20.7	20.1	20.3	20.3	20.1
G_{Late} (dB)	12.4	16.9	12.8	11.9	12.0	12.7	12.0	11.1	8.2
LF	0.16	0.28	0.12	0.18	0.19	0.16	0.12	0.15	1.44
BR	0.85								
TR	0.85								
* Measurement A2 at 125 Hz excluded from T30 and T20 reverberation time averages due to very high values (~3.9 seconds) measured not observed at other positions.									
Cross-stage measurements (A3) – only one position measured due to small stage dimensions									
EDT (s)	1.57	1.39	1.10	1.30	1.57	1.57	1.47	1.17	0.88
T_{20} (s)	1.63	1.09	1.12	1.17	1.58	1.68	1.54	1.27	0.96
T_{30} (s)	1.65	1.16	1.14	1.32	1.59	1.71	1.56	1.28	1.00
C_{80} (dB)	0.1	0.2	–0.3	–0.2	0.7	–0.5	1.1	2.2	4.5
C_{50} (dB)	–2.2	–1.5	–4.8	–2.0	–1.5	–2.8	–1.2	–1.0	0.8
G (dB)	14.8	15.5	15.9	14.3	14.6	15.1	14.5	14.6	12.8
G_{80} (dB)	11.8	13.7	12.6	11.2	11.9	11.8	12.0	12.4	11.5
G_{Late} (dB)	11.7	13.5	12.9	11.4	11.1	12.3	10.9	10.3	7.0
BR	0.75								
TR	0.84								
Conductor's position measurement (D1)									
EDT (s)	1.55	1.49	1.31	1.24	1.49	1.60	1.46	1.21	0.86
T_{20} (s)	1.68	2.27	1.29	1.28	1.63	1.72	1.55	1.28	0.97
T_{30} (s)	1.69	2.33	1.27	1.26	1.61	1.77	1.54	1.30	1.01
C_{80} (dB)	0.7	–2.0	3.5	2.0	1.1	0.3	0.7	3.1	5.4

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	63	125	250	500	1000	2000	4000	8000
C_{50} (dB)	–1.8	–5.9	–0.9	–0.5	–1.2	–2.4	–2.3	0.1	1.6
G (dB)	14.7	14.6	14.4	13.5	14.6	14.9	14.5	14.7	13.4
G_{80} (dB)	12.0	11.0	12.9	11.4	12.1	12.0	11.8	13.0	12.2
G_{Late} (dB)	11.3	13.0	9.4	9.3	11.0	11.7	11.1	9.9	6.9
LF	0.40	0.78	0.24	0.42	0.53	0.39	0.29	0.31	2.61
BR	0.75								
TR	0.84								

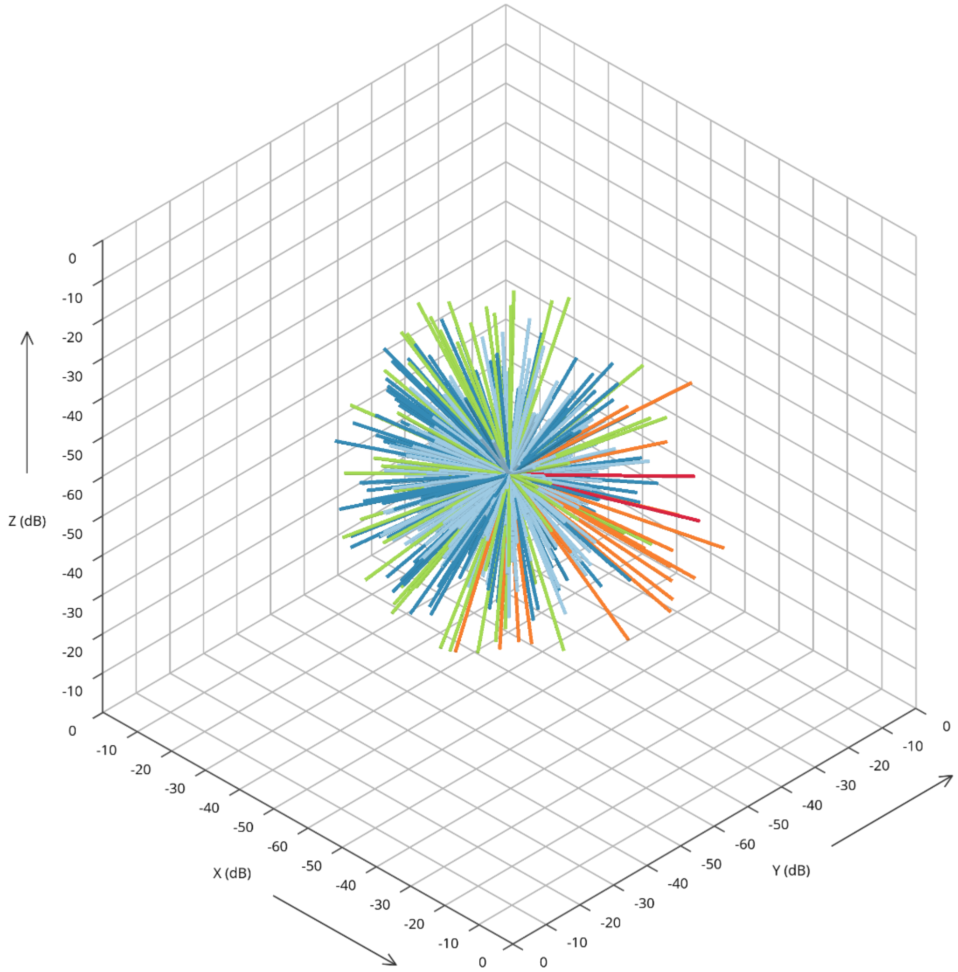


Figure 42: RUC measurement B1 IRIS 3-D sound intensity vector plot

E5 Holy Trinity Anglican Church

Table 17: HTA averaged acoustic measurements

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	63	125	250	500	1000	2000	4000	8000
1m measurements (positions A1, A2, C1, C2) – small stage geometry didn't allow for measurements in position B									
T_{20} (s)	1.74	1.16	1.55	1.90	1.81	1.67	1.51	1.23	0.87
T_{30} (s)	1.78	1.26	1.75	1.81	1.84	1.71	1.59	1.32	0.98
ST_{Early} (dB)	–13.5	2.8	–5.7	–14.3	–14.0	–12.9	–12.7	–12.7	–13.2
ST_{Late} (dB)	–13.5	–	–5.9	–13.1	–12.6	–12.5	–13.9	–15.3	–
C_{80} (dB)	11.9	13.0	13.8	13.4	11.9	12.0	13.0	14.3	16.5
C_{50} (dB)	11.1	10.9	13.2	12.9	11.2	11.1	11.6	12.7	14.8
G (dB)	19.4	22.9	24.4	21.2	19.9	18.9	19.3	18.9	18.9
G_{80} (dB)	19.1	22.8	24.2	21.0	19.5	18.8	19.0	18.7	18.8
G_{Late} (dB)	7.3	10.0	10.7	8.2	7.7	6.9	6.0	4.5	2.2
LF	0.05	0.17	0.04	0.05	0.06	0.05	0.04	0.04	0.38
BR	1.00								
TR	0.82								
Cross-stage measurement (A3) – small stage geometry didn't allow for measurements in position B									
EDT (s)	1.86	0.82	0.97	1.81	1.99	1.74	1.70	1.33	0.99
T_{20} (s)	1.85	1.35	1.69	1.74	1.89	1.80	1.63	1.38	1.07
T_{30} (s)	1.85	1.38	1.67	1.79	1.89	1.80	1.66	1.38	1.10
C_{80} (dB)	2.7	4.8	–4.0	2.7	3.5	2.0	2.0	4.4	5.8
C_{50} (dB)	0.6	1.9	–6.0	1.2	1.5	–0.3	–0.4	1.7	2.8
G (dB)	10.0	15.0	13.3	11.0	10.9	9.1	8.9	8.8	7.4
G_{80} (dB)	8.2	14.0	7.7	9.2	9.2	7.2	6.7	7.4	6.4
G_{Late} (dB)	5.5	9.3	11.7	6.5	5.7	5.2	4.7	3.0	0.5
BR	0.94								
TR	0.82								
Conductor's position measurement (D1)									
EDT (s)	1.84	1.26	1.60	2.23	1.90	1.78	1.75	1.50	1.20
T_{20} (s)	1.77	0.99	1.56	1.81	1.82	1.72	1.64	1.41	1.09
T_{30} (s)	–	1.07	1.67	1.75	–	1.73	1.67	1.44	1.11
C_{80} (dB)	0.2	–1.7	–0.8	3.1	0.3	0.1	0.9	3.2	4.5
C_{50} (dB)	–2.5	–2.3	–2.8	2.1	–1.8	–3.2	–2.0	0.7	2.4

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	63	125	250	500	1000	2000	4000	8000
G (dB)	9.7	14.6	11.1	12.1	10.1	9.3	8.5	8.1	5.9
G_{80} (dB)	6.7	11.6	7.5	10.4	7.1	6.3	5.9	6.5	4.6
G_{Late} (dB)	6.4	13.2	8.3	7.3	6.7	6.1	5.0	3.2	0.1
LF	0.06	0.03	0.05	0.02	0.10	0.08	0.12	0.12	1.18
BR	0.96 *								
TR	0.88 *								

* BR and TR calculated based on T_{20} 500 Hz value where T_{30} value not available.

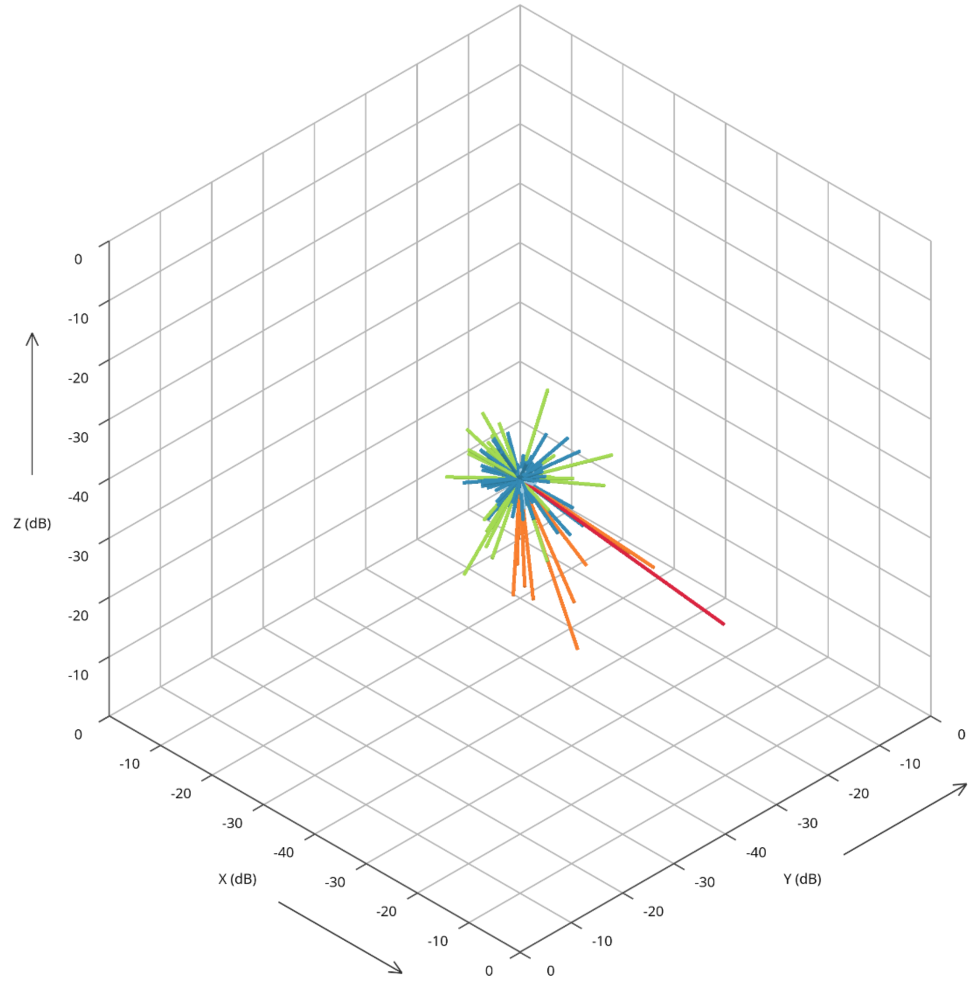


Figure 43: HTA measurement C1 IRIS 3-D sound intensity vector plot

E6 St Paul’s Cathedral

Table 18: SPC averaged acoustic measurements

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	63	125	250	500	1000	2000	4000	8000
1m measurements (positions A1, A2, B1, B2, C1, C2)									
T_{20} (s)	1.88	1.47	1.75 *	1.93	1.96	1.79	1.60	1.15	0.86
T_{30} (s)	2.31	1.44	2.14 *	2.35 †	2.36	2.26	1.95	1.48	1.07
ST_{Early} (dB)	–13.5	4.3	–4.4	–13.4	–13.2	–12.4	–14.4	–13.3	–12.8
ST_{Late} (dB)	–14.9	–	–9.5	–13.9	–15.2	–14.4	–15.9	–17.3	–17.9
C_{80} (dB)	14.5	12.3	14.6	13.9	15.0	14.2	15.6	17.0	17.0
C_{50} (dB)	13.2	9.6	13.1	12.7	13.8	12.7	13.8	15.1	14.6
G (dB)	19.7	23.7	23.6	20.6	20.0	19.4	19.8	20.9	19.0
G_{80} (dB)	19.5	23.7	23.5	20.4	20.0	19.1	19.7	20.7	18.9
G_{Late} (dB)	5.0	12.1	9.1	6.6	5.1	5.0	4.1	3.7	2.0
LF	0.05	0.08	0.06	0.05	0.04	0.04	0.04	0.05	0.43
BR	0.97								
TR	0.74								
* Measurements A2 125 Hz reverberation time excluded from T_{20} (6.04 secs) and T_{30} (6.83 secs) averages due to very high values measured, not observed at other positions.									
† Measurement A1 250 Hz reverberation time excluded from T_{30} (4.56 secs) average due to very high values measured, not observed at other positions.									
Cross-stage measurements (A3, B3)									
EDT (s)	1.81	1.86	1.69	1.92	1.89	1.73	1.56	1.10	0.78
T_{20} (s)	2.26	2.26	2.14	2.24	2.27	2.25	1.99	1.56	1.07
T_{30} (s)	2.35	–	2.19	2.42	2.31	2.38	2.14	1.69	1.21
C_{80} (dB)	3.2	4.0	2.9	2.0	2.9	3.4	4.1	6.5	9.1
C_{50} (dB)	1.7	–1.9	–3.0	0.6	1.2	2.3	2.6	4.0	6.4
G (dB)	9.8	14.8	12.7	10.7	10.1	9.6	9.5	10.2	10.3
G_{80} (dB)	8.2	13.5	10.9	8.6	8.4	7.9	8.1	9.3	9.8
G_{Late} (dB)	4.9	9.5	8.0	6.4	5.4	4.4	4.0	2.9	0.7
BR	0.98								
TR	0.82								
Conductor’s position measurement (D1)									
EDT (s)	1.78	1.45	1.53	1.97	1.78	1.78	1.75	1.46	0.92
T_{20} (s)	2.42	2.40	2.11	2.15	2.50	2.34	2.12	1.70	1.30

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
T_{30} (s)	2.85	2.60	2.23	2.26	3.22	2.49	2.26	1.78	1.40
C_{80} (dB)	0.9	0.0	1.9	–1.2	0.0	1.7	2.8	5.0	8.7
C_{50} (dB)	–1.0	–2.7	–3.1	–3.1	–2.1	0.1	1.2	3.6	6.7
G (dB)	8.5	10.8	11.8	9.5	9.3	7.7	7.6	6.1	5.2
G_{80} (dB)	5.6	8.1	9.7	6.0	5.9	5.4	5.7	4.9	4.6
G_{Late} (dB)	4.8	8.1	7.9	7.2	5.8	3.7	3.0	–0.1	–4.0
LF	0.04	0.02	0.02	0.03	0.03	0.08	0.10	0.14	0.55
BR	0.79								
TR	0.71								

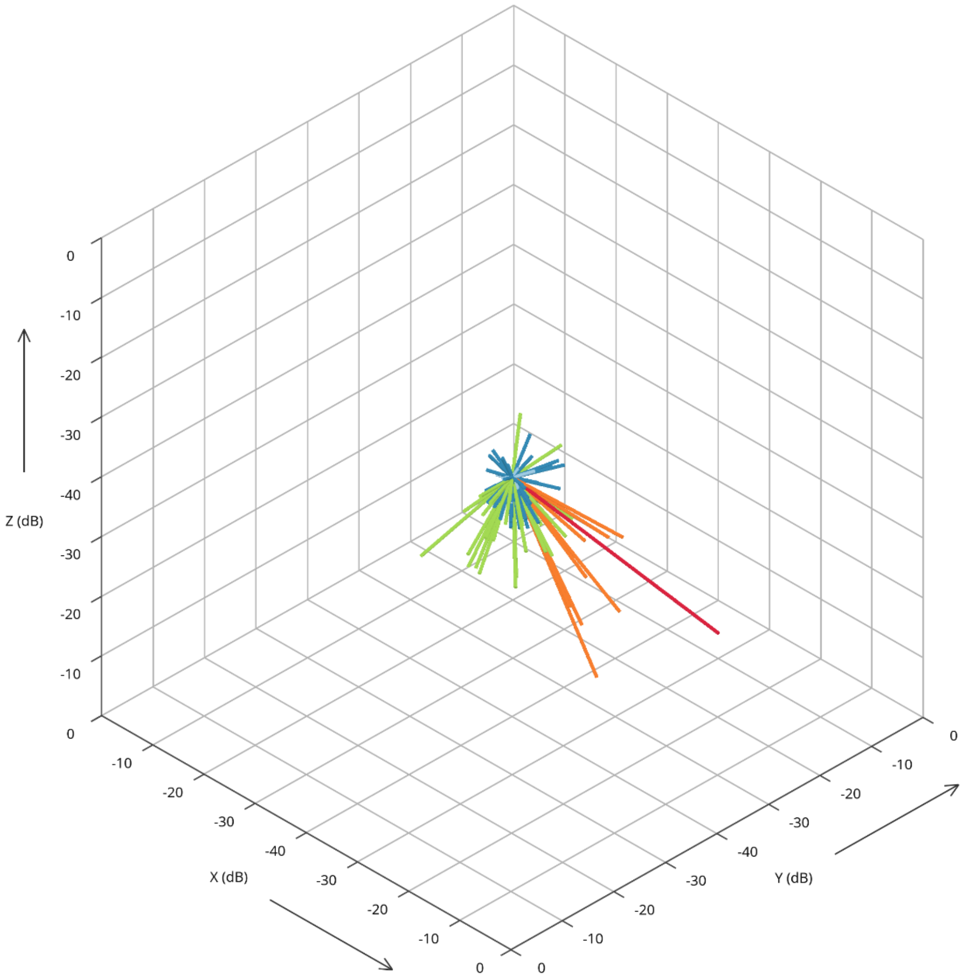


Figure 44: SPC measurement B1 IRIS 3-D sound intensity vector plot

E7 Dorothy Pizzey Centre, St Catherine’s School

Table 19: DPC averaged acoustic measurements

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	63	125	250	500	1000	2000	4000	8000
1m measurements (positions A1, A2, B1, B2, C1, C2)									
T_{20} (s)	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
T_{30} (s)	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
ST_{Early} (dB)	–9.1	3.7	–5.2	–10.8	–8.0	–8.3	–8.4	–11.6	–10.8
ST_{Late} (dB)	–	–	–	–15.8	–11.2	–10.6	–12.6	–16.7	–16.7
C_{80} (dB)	12.0	12.2	14.0	13.6	11.8	12.3	12.9	15.9	16.9
C_{50} (dB)	10.0	8.5	11.9	11.8	9.9	10.2	11.0	13.7	14.1
G (dB)	19.2	23.5	23.6	20.6	19.6	18.9	19.7	21.4	18.8
G_{80} (dB)	18.7	23.4	23.4	20.3	18.8	18.7	19.4	21.2	18.6
G_{Late} (dB)	7.3	11.7	9.7	6.9	7.3	7.4	7.5	5.8	2.1
LF	0.04	0.12	0.05	0.03	0.05	0.03	0.03	0.02	0.24
BR	0.81								
TR	0.96								
Cross-stage measurements (A3, B3)									
EDT (s)	1.20	0.98	1.34	1.03	1.09	1.31	1.23	1.14	0.85
T_{20} (s)	1.49	1.31	1.53	1.42	1.45	1.53	1.50	1.29	0.96
T_{30} (s)	1.57	–	1.34	1.48	1.56	1.58	1.64	1.43	1.04
C_{80} (dB)	4.4	3.6	1.7	6.6	4.9	4.0	5.0	7.7	9.4
C_{50} (dB)	2.0	1.0	–0.3	4.7	2.2	1.8	1.6	5.1	6.4
G (dB)	11.1	14.4	13.1	12.8	11.5	10.6	10.9	12.0	10.4
G_{80} (dB)	9.6	13.0	10.8	11.8	10.2	9.1	9.7	11.4	10.0
G_{Late} (dB)	5.4	9.7	9.4	5.7	5.6	5.2	4.7	3.4	0.2
BR	0.90								
TR	0.98								
Conductor’s position measurement (D1)									
EDT (s)	1.14	1.22	1.02	0.84	0.93	1.36	1.50	0.96	0.83
T_{20} (s)	1.30	1.48	1.24	1.18	1.26	1.35	1.39	1.28	0.95
T_{30} (s)	1.33	–	1.24	1.25	1.32	1.35	1.41	1.27	0.98
C_{80} (dB)	3.8	2.2	2.1	4.5	4.4	3.1	2.9	5.5	6.8
C_{50} (dB)	1.0	0.7	–1.1	1.4	1.2	0.8	1.1	3.0	4.6

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	63	125	250	500	1000	2000	4000	8000
G (dB)	11.0	13.3	14.2	11.7	12.2	9.9	8.7	9.7	8.2
G_{80} (dB)	9.5	11.7	12.2	10.3	10.9	8.2	6.7	8.7	7.3
G_{Late} (dB)	5.8	9.6	10.1	5.9	6.4	5.1	3.9	3.2	0.5
LF	0.06	0.02	0.02	0.03	0.05	0.13	0.23	0.11	1.48
BR	0.79								
TR	0.71								

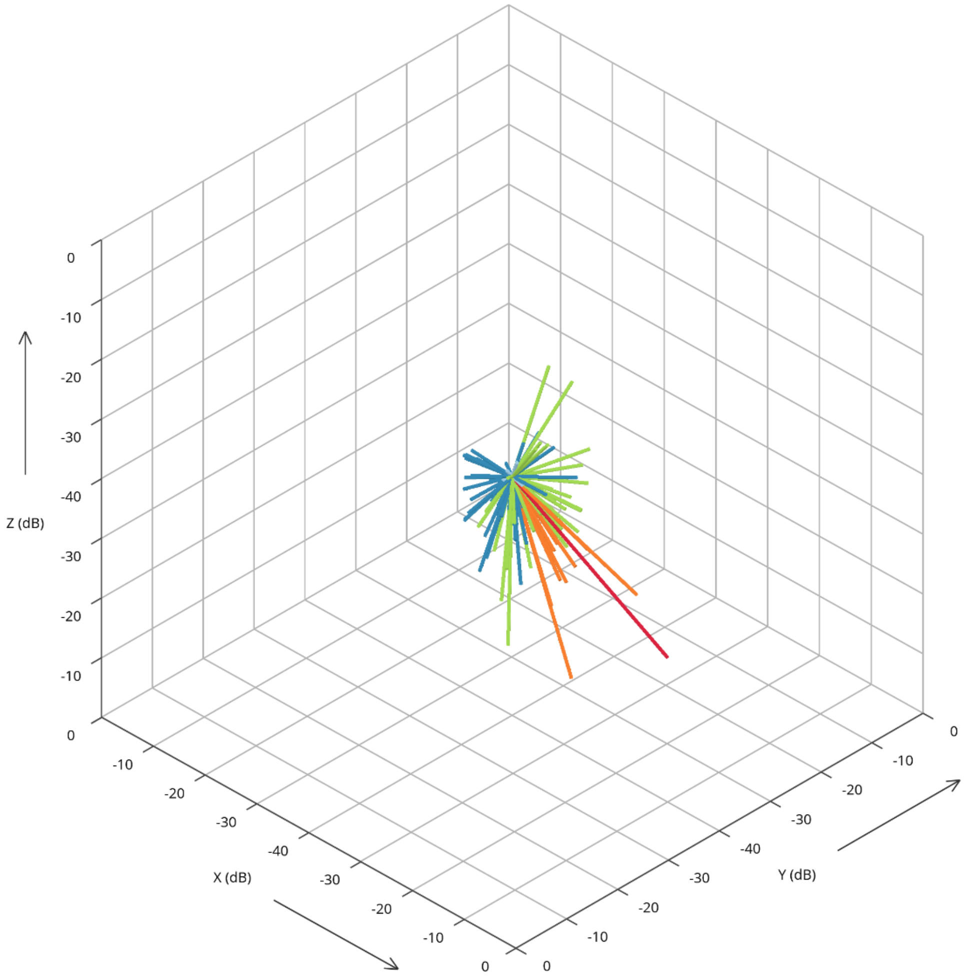


Figure 45: DPC measurement B1 IRIS 3-D sound intensity vector plot

E8 Christ Church St Laurence

Table 20: CSL averaged acoustic measurements

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	63	125	250	500	1000	2000	4000	8000
1m measurements (positions A1, A2, B1, B2, C1, C2)									
T_{20} (s)	2.39	1.43	1.74	1.95	2.27	2.50	2.27	1.58	0.97
T_{30} (s)	2.47	1.48	1.82	1.97	2.34	2.60	2.41	1.77	1.17
ST_{Early} (dB)	–10.9	–1.3	–6.4	–10.8	–11.2	–9.9	–11.0	–11.0	–11.7
ST_{Late} (dB)	–10.1	–	–8.9	–11.0	–10.2	–8.7	–10.3	–12.7	–16.0
C_{80} (dB)	10.1	11.7	13.7	12.3	11.0	9.2	10.6	14.4	16.2
C_{50} (dB)	8.9	8.5	12.3	11.1	9.9	8.0	9.5	12.8	14.1
G (dB)	21.9	24.4	25.2	22.8	22.1	21.7	22.5	24.9	23.5
G_{80} (dB)	21.6	24.6	25.1	22.5	22.0	21.3	22.1	24.7	23.3
G_{Late} (dB)	11.6	13.7	11.7	10.4	11.1	12.2	11.6	10.3	7.2
LF	0.07	0.09	0.06	0.05	0.09	0.10	0.07	0.08	0.79
BR	0.77								
TR	0.85								
Cross-stage measurements (A3, B3)									
EDT (s)	2.37	0.66	1.49	1.86	2.45	2.30	2.21	1.45	0.97
T_{20} (s)	2.49	1.59	2.01	2.10	2.29	2.69	2.50	1.81	1.27
T_{30} (s)	2.52	–	1.93	2.11	2.35	2.69	2.51	1.89	1.34
C_{80} (dB)	–1.4	7.5	3.0	–1.6	–1.4	–1.4	–0.1	3.8	5.3
C_{50} (dB)	–3.5	4.8	–0.1	–4.8	–3.3	–3.6	–2.5	1.7	2.5
G (dB)	13.4	16.9	14.1	11.4	12.9	14.0	13.8	15.2	12.3
G_{80} (dB)	9.6	16.4	12.2	7.6	9.1	10.2	10.8	13.7	11.1
G_{Late} (dB)	11.0	9.0	9.4	9.2	10.5	11.6	10.9	9.9	5.8
BR	0.80								
TR	0.87								
Conductor's position measurement (D1 averaged with repeat measurement)									
EDT (s)	2.26	0.74	1.51	1.65	2.19	2.33	2.49	1.67	0.40
T_{20} (s)	2.45	1.08	1.79	2.05	2.33	2.57	2.48	1.85	1.21
T_{30} (s)	2.49	1.12	1.91	2.04	2.38	2.60	2.50	1.90	1.29
C_{80} (dB)	3.5	6.8	2.8	6.9	3.7	3.3	4.7	5.5	11.4
C_{50} (dB)	2.5	2.1	0.6	6.3	2.7	2.3	4.0	4.3	9.9

Parameter (unit)		Octave-band centre Frequency (Hz)							
	Mid	63	125	250	500	1000	2000	4000	8000
G (dB)	17.0	19.9	17.5	18.0	17.0	17.0	16.8	16.3	17.9
G_{80} (dB)	15.4	19.1	15.7	17.2	15.4	15.4	15.5	15.1	17.6
G_{Late} (dB)	11.9	12.3	12.8	10.3	11.7	12.2	10.8	9.6	6.2
LF	0.09	0.06	0.08	0.06	0.08	0.13	0.09	0.27	1.05
BR	0.79								
TR	0.88								

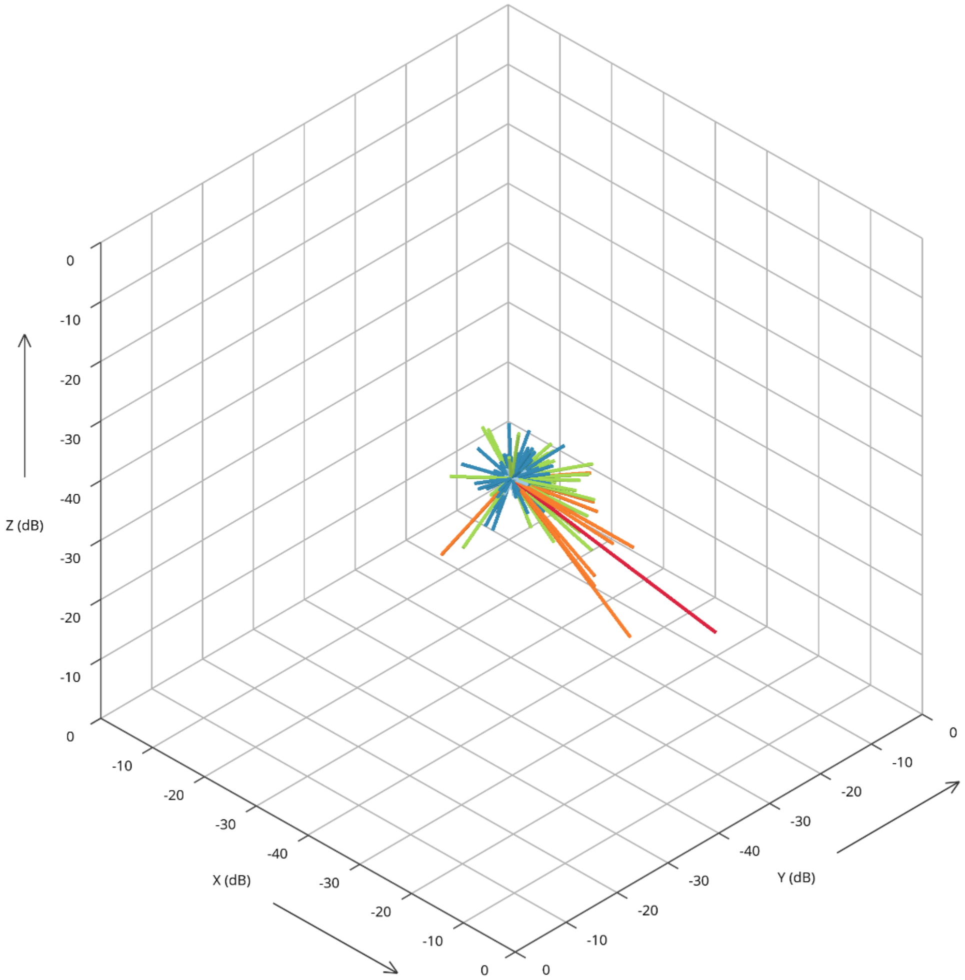


Figure 46: CSL measurement B1 IRIS 3-D sound intensity vector plot

APPENDIX F VENUE PHOTOS AND ARCHITECTURAL DRAWINGS

This appendix contains photos and architectural drawings of the venues in this study.

Architectural drawings have been sourced from the venues or relevant archives.

Photos are generally taken by the author, specifically where the source has not been credited in the caption. Photos taken by other parties have been credited, and permission has been obtained to reproduce them.

F1 St Matthew-in-the-City

Figure 47: St Matthew-in-the-City – interior of church facing chancel

Figure 48: St Matthew-in-the-City – interior of church facing nave

The following drawing has been provided by St Matthew-in-the-City.

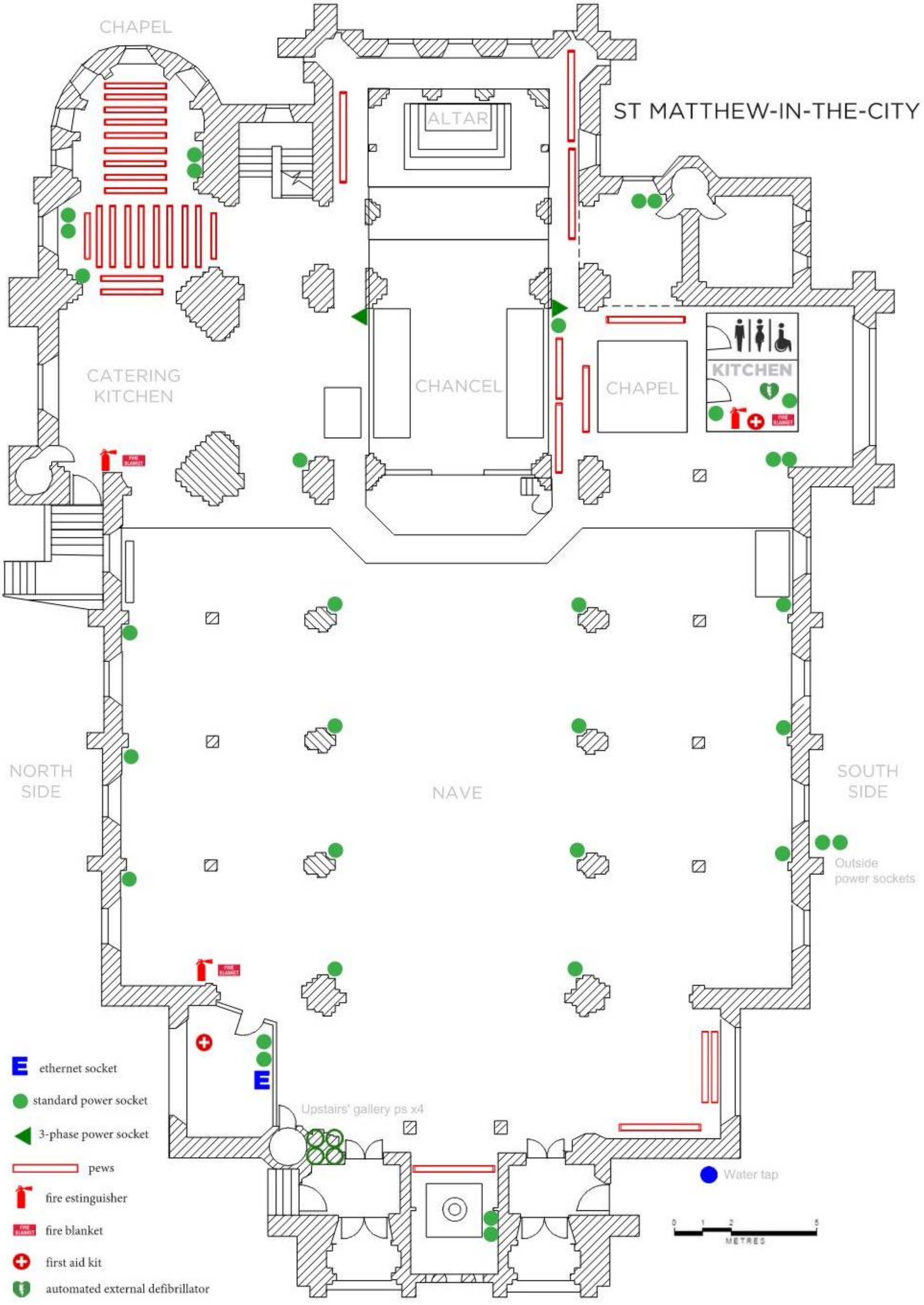


Figure 49: St Matthew-in-the-City floor plan

The following drawings have been prepared and provided by Salmond Reed Architects.

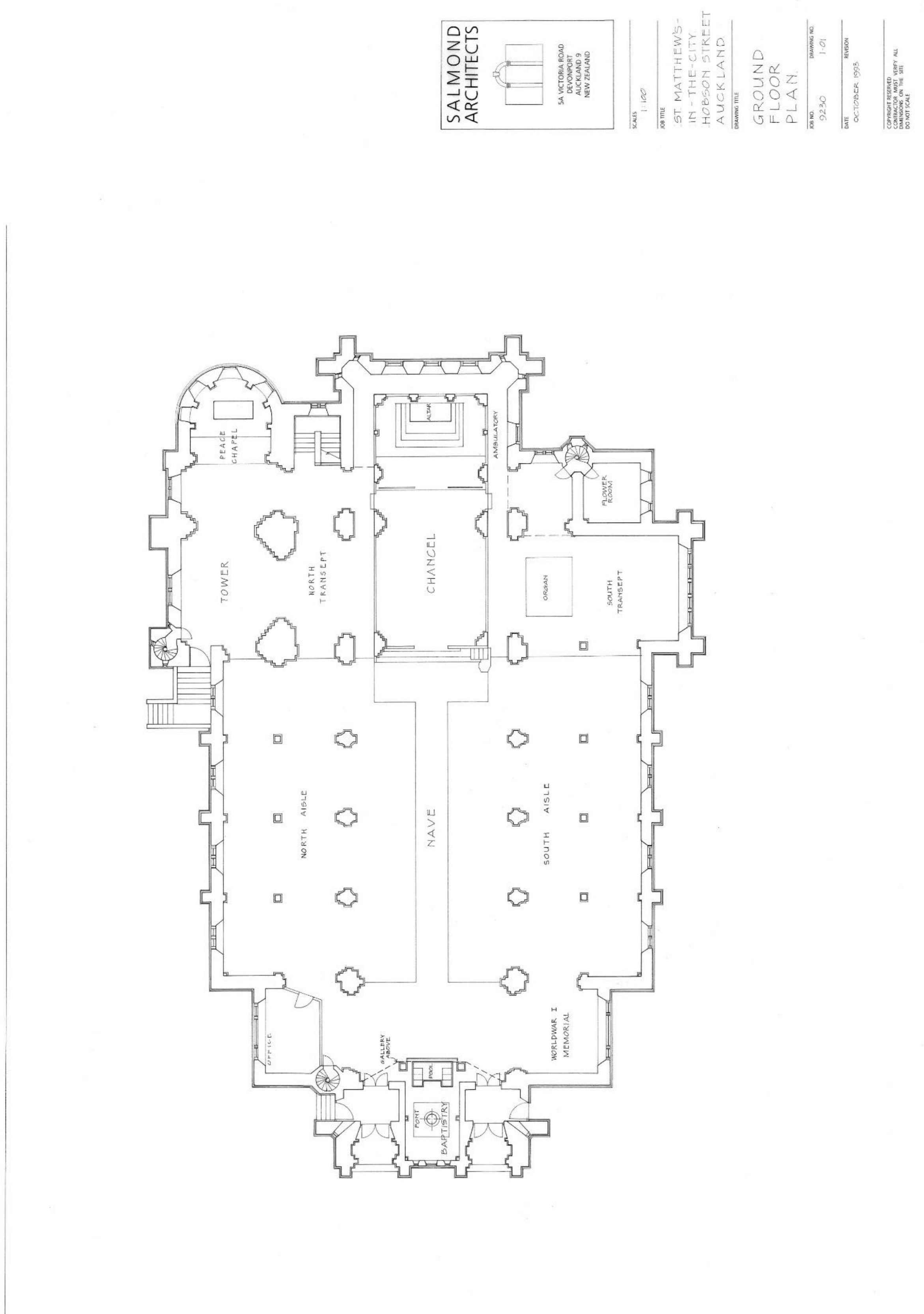


Figure 50: St Matthew-in-the-City – Ground Floor Plan

Figure 51: St Matthew-in-the-City – Section View looking North

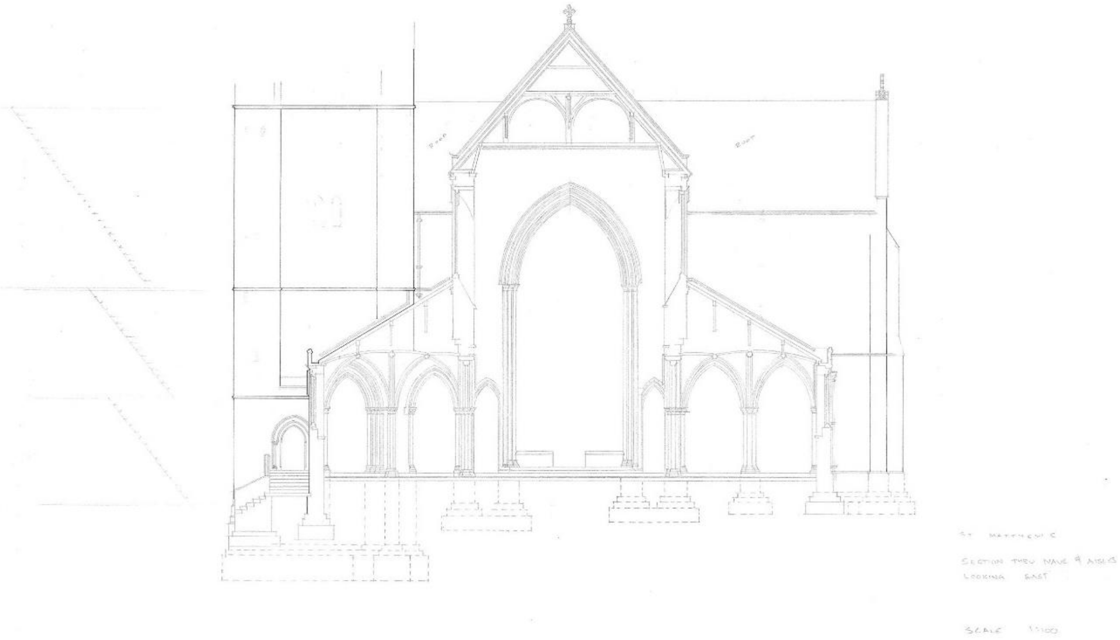


Figure 52: St Matthew-in-the-City – Section through Nave & Aisles looking East

Figure 53: St Matthew-in-the-City – Section through Nave & Aisles looking West

F2 The Farrall Centre, The Friends' School

Figure 54: The Farrall Centre – interior of auditorium facing stage

Figure 55: The Farrall Centre – interior of auditorium facing audience seating

The following drawings have been prepared by IDW Architecture + Interiors, and provided by The Farrall Centre.

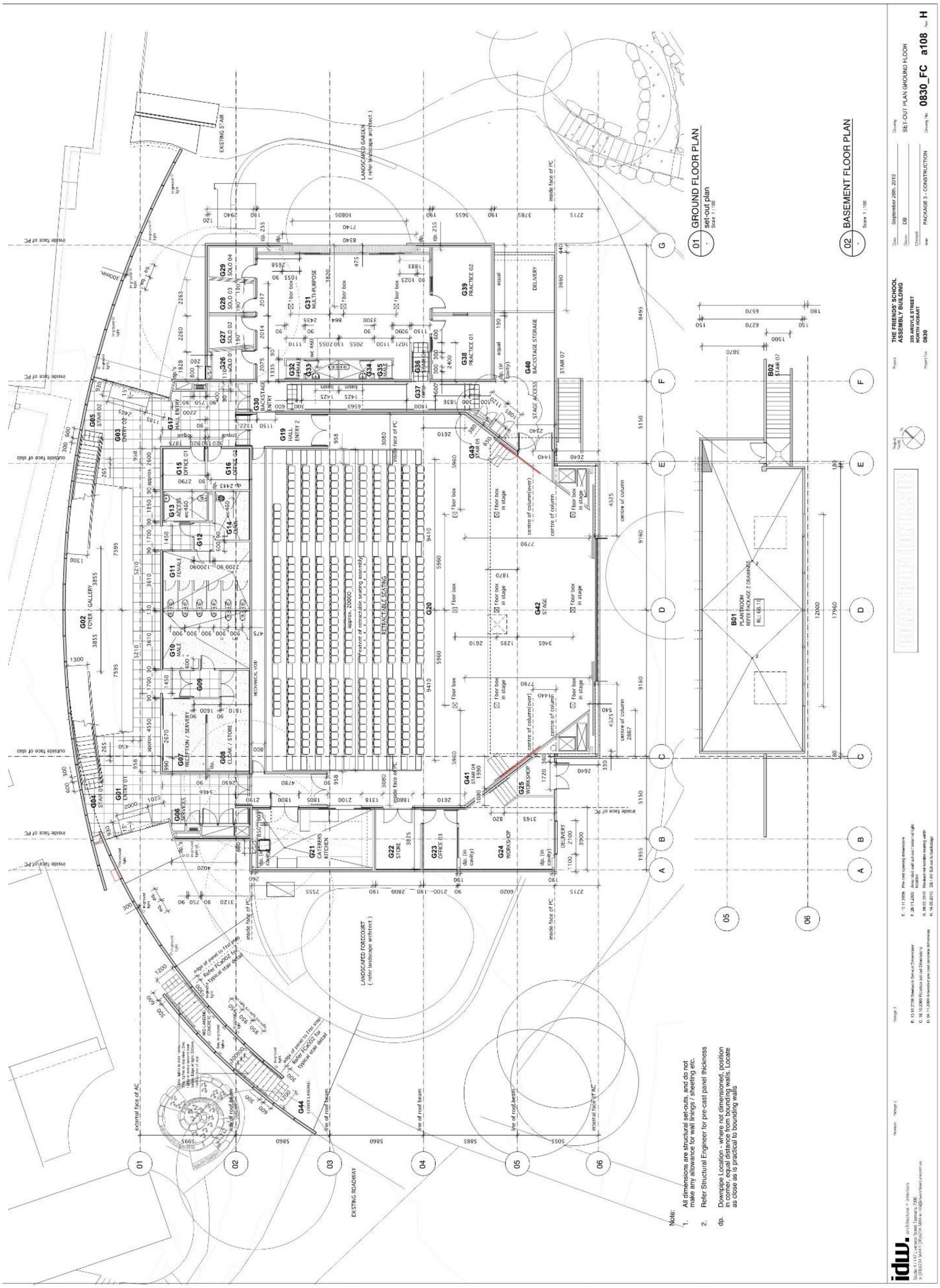


Figure 56: The Farrall Centre – Set-out Plan Ground Floor

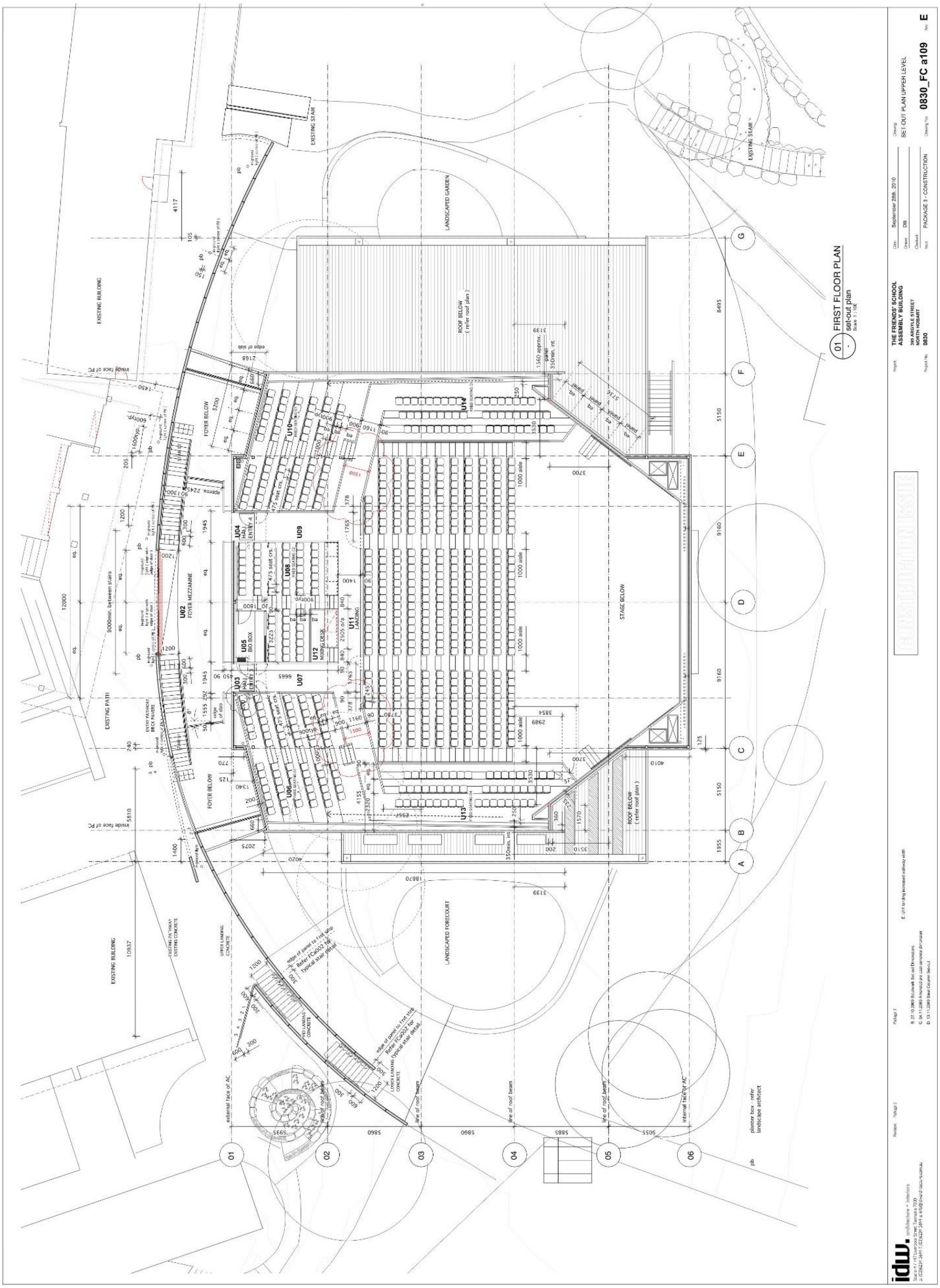


Figure 57: The Farrall Centre – Set-out Plan Upper Level

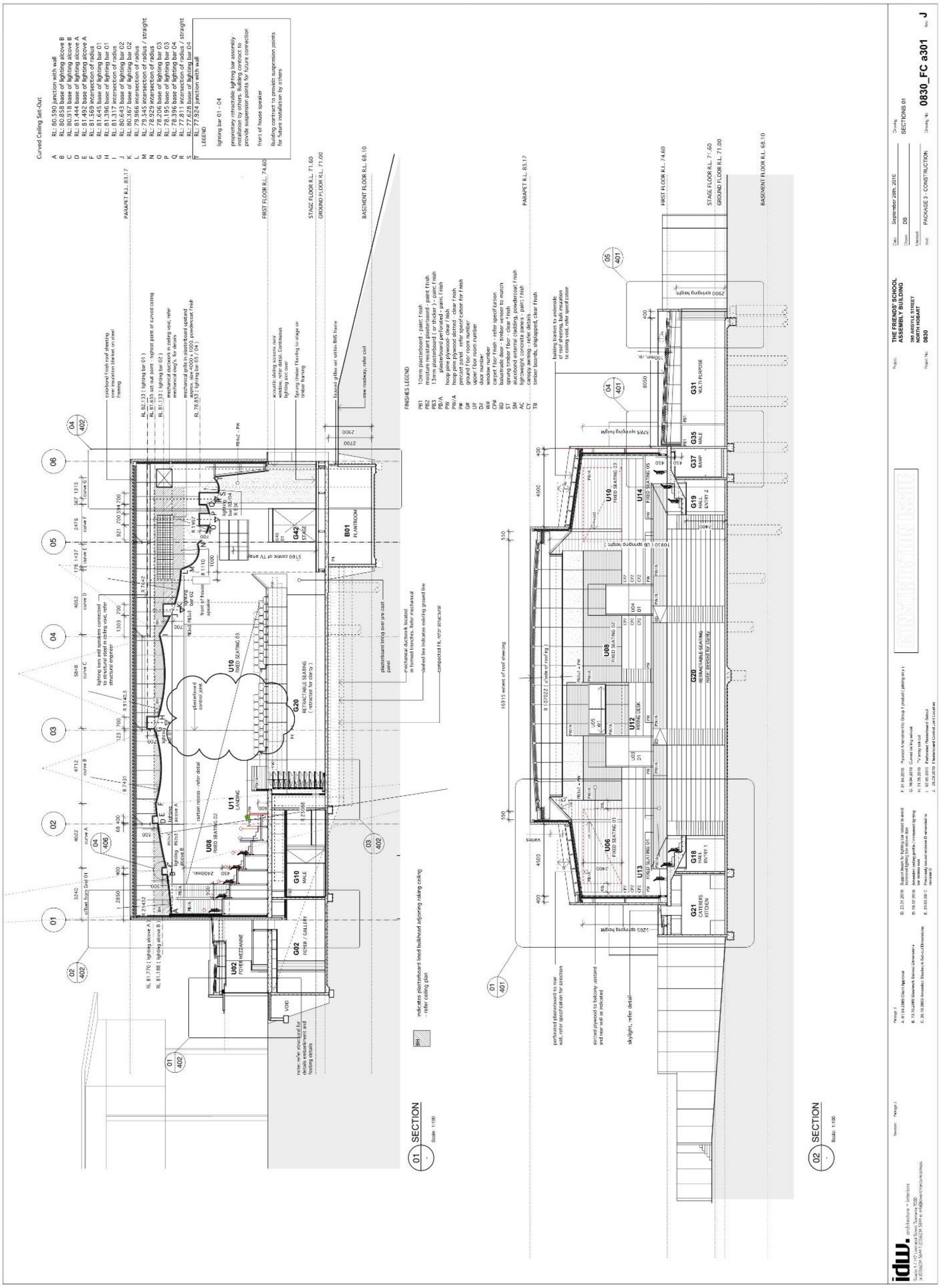


Figure 58: The Farrall Centre – Sections 01

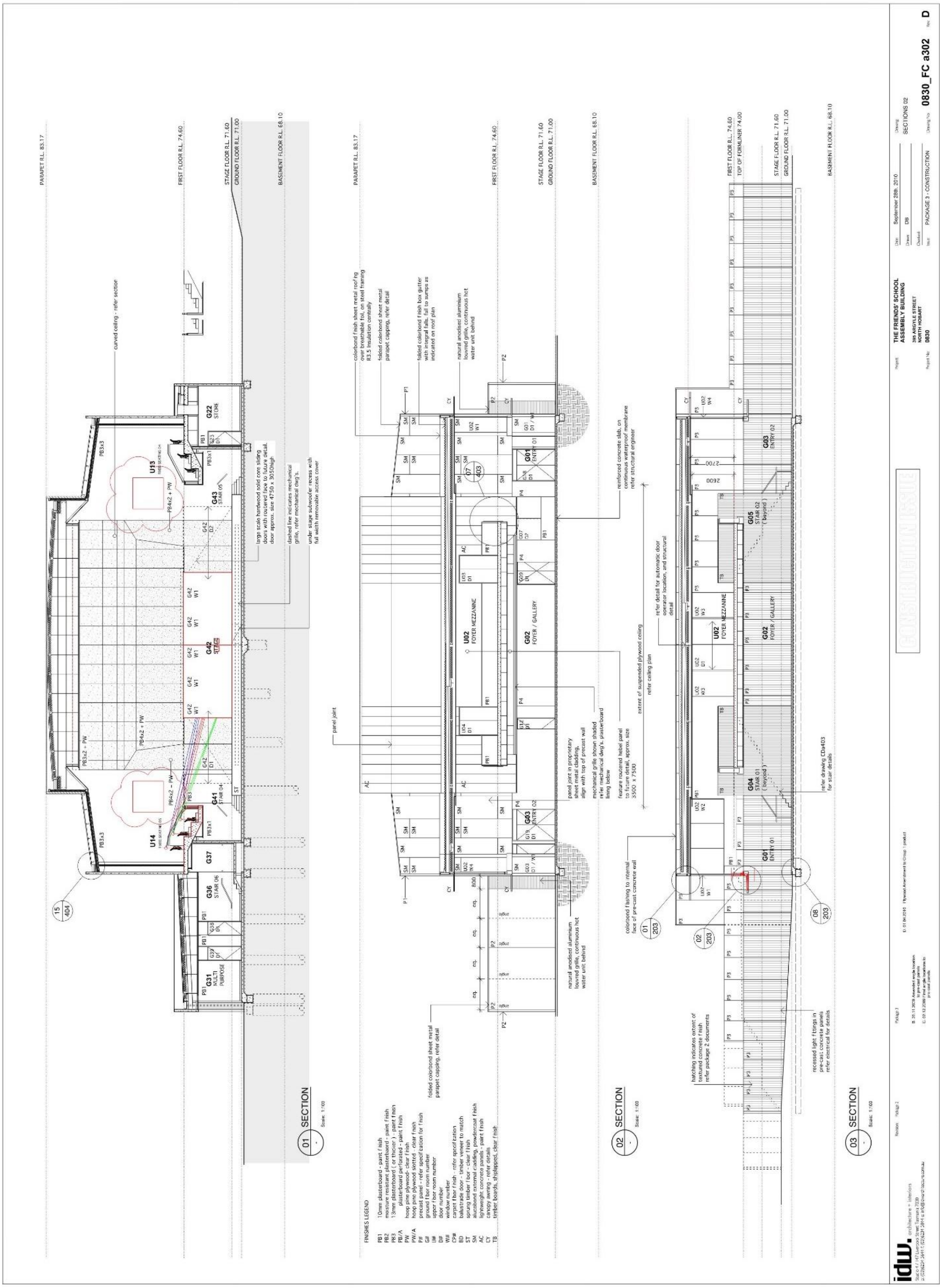


Figure 59: The Farrall Centre – Sections 02

F3 St David's Cathedral

Figure 60: St David's Cathedral – interior of church facing chancel

Figure 61: St David's Cathedral – interior of church facing nave

The following drawing has been provided by St David's Cathedral.

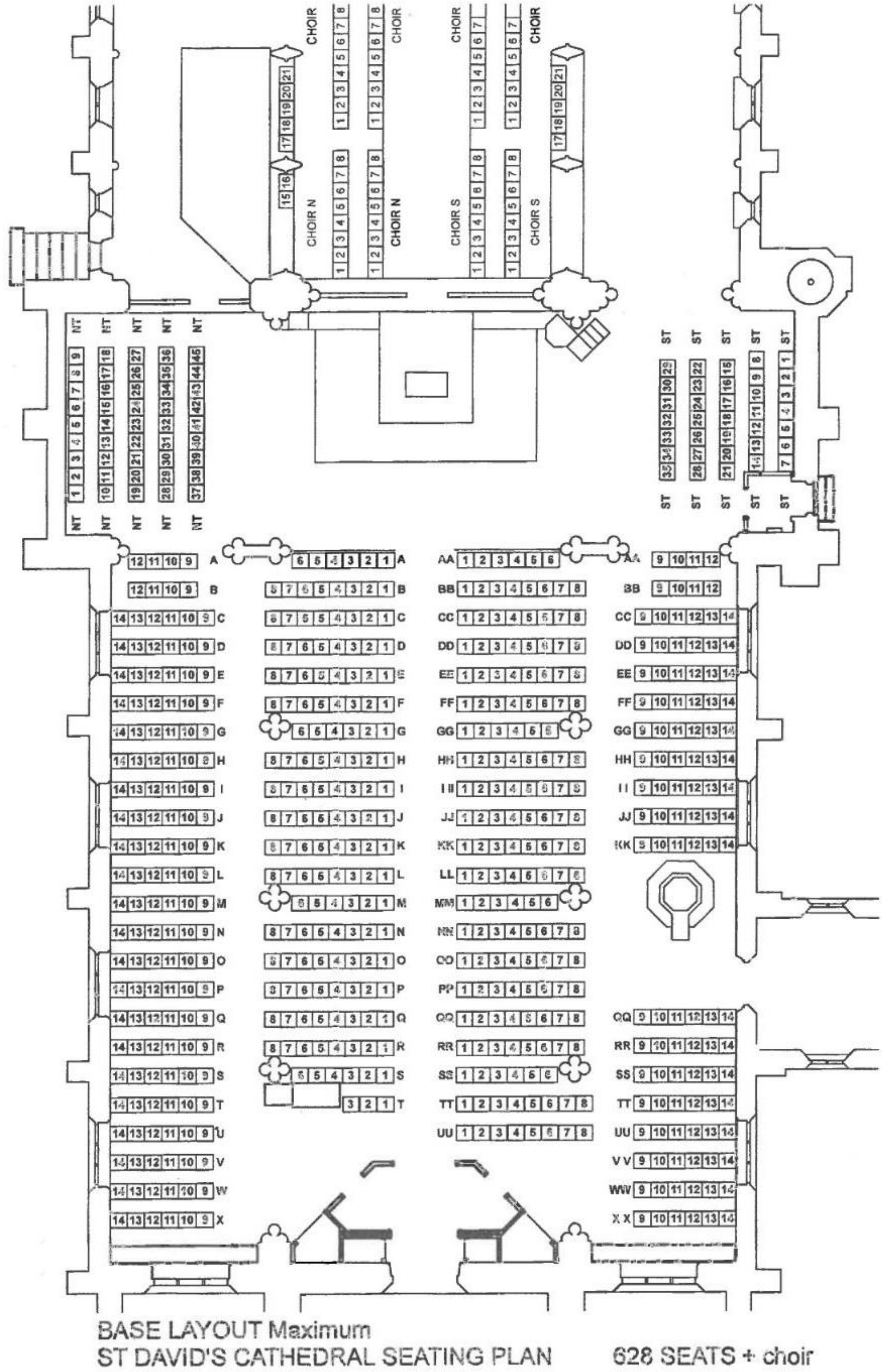


Figure 62: St David's Cathedral – seating plan

The following architectural drawings have been provided by Architects Designhaus.

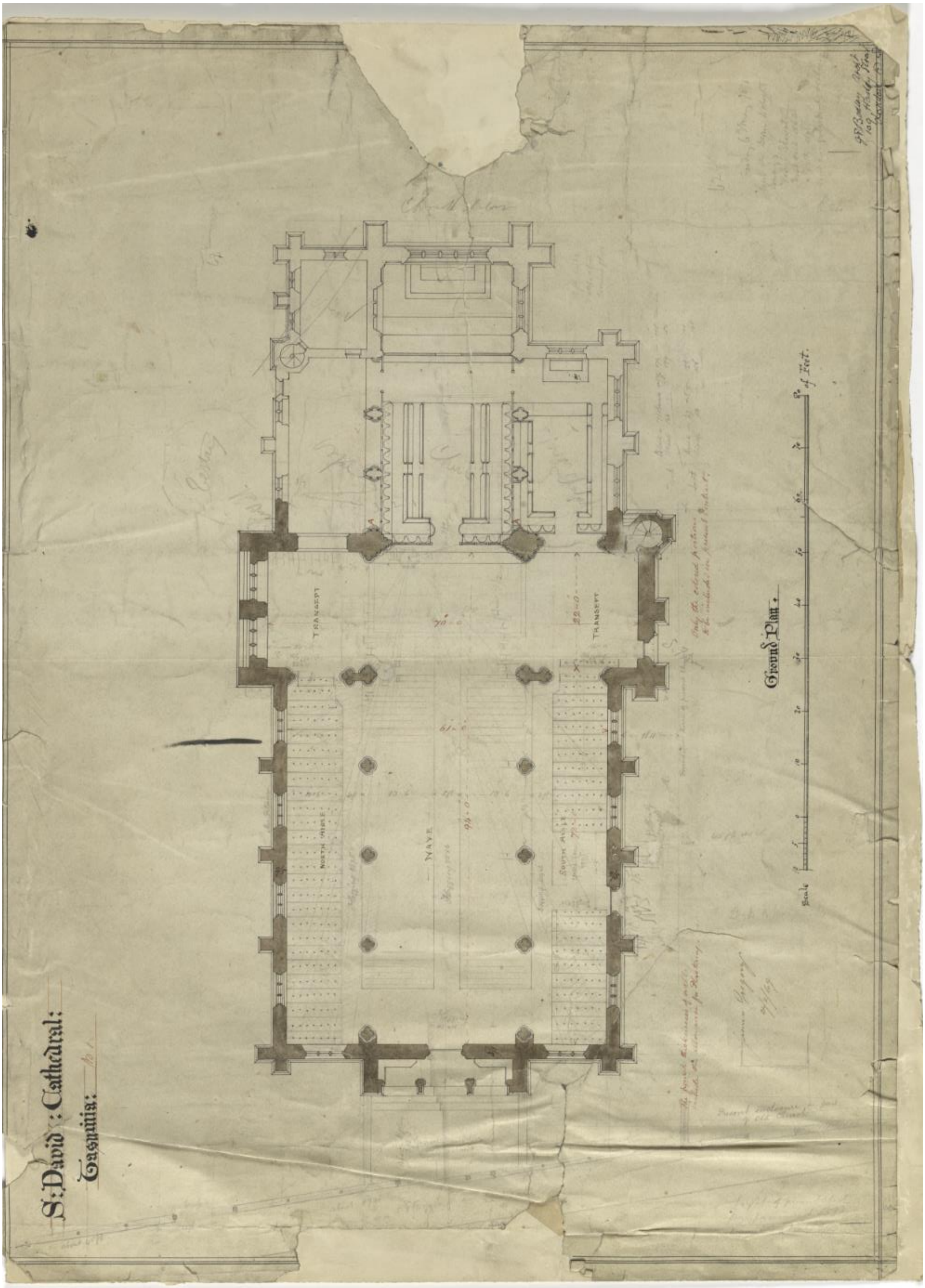


Figure 63: St David's Cathedral – Ground Plan

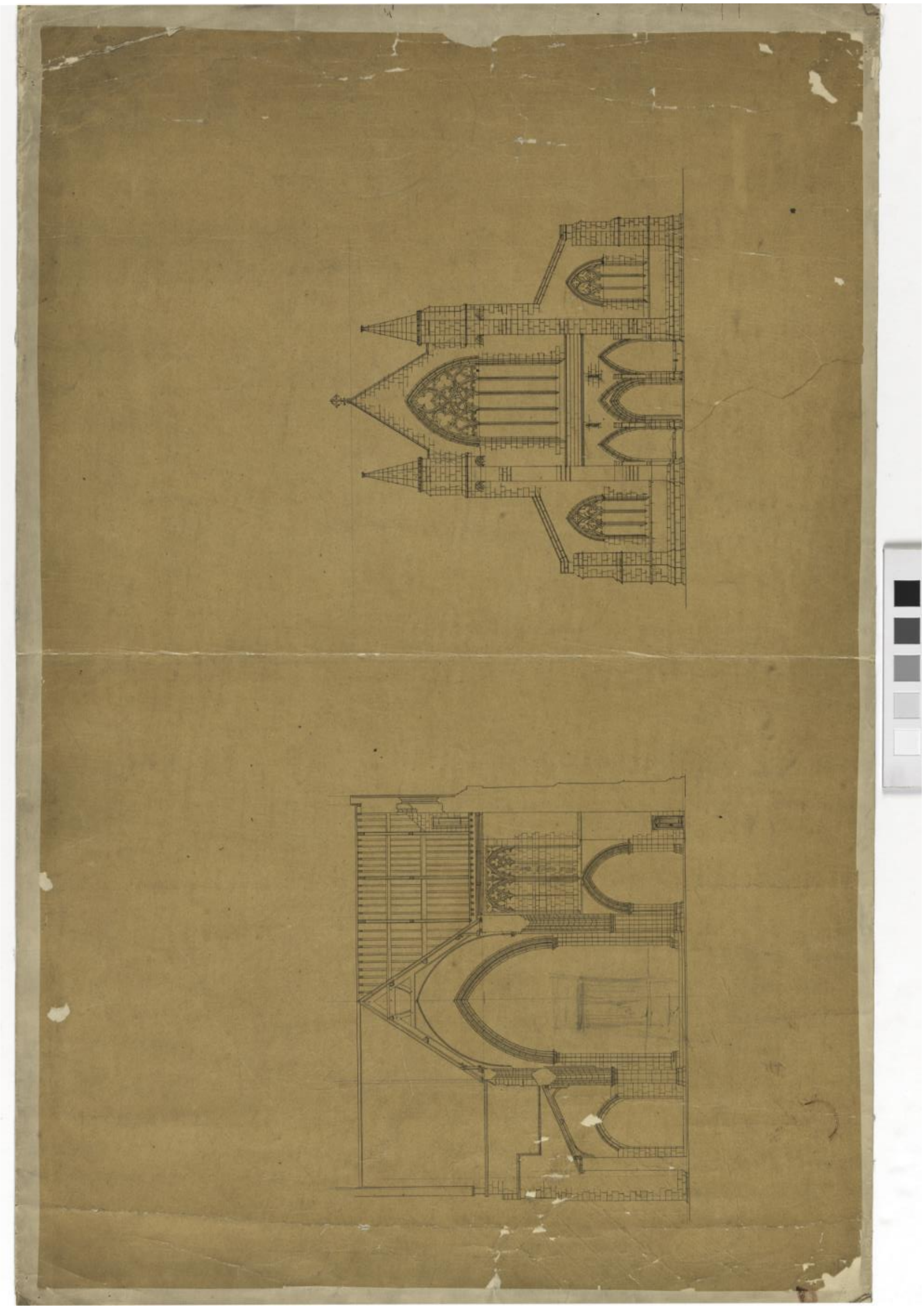


Figure 64: St David’s Cathedral – West elevation and short section through nave

F4 Ross Uniting Church

Figure 65: Ross Uniting Church – interior of church facing pulpit (Photography: John Huth[9])

Figure 66: Ross Uniting Church – interior of church facing nave (Source: Monissa's Place[10])

---

[9] Ross Uniting Church churchesaustralia.org/list-of-churches/locations/tasmania/directory/1169-ross-uniting-church

[10] Wesleyan/Uniting Church, Ross monissa.com/ccphotos/wesleyan-now-uniting-church-ross/

The following architectural sketches have been prepared by the author. Note that these show the internal volume of the performance space only, and are not representative of external geometry. Dimensions were measured on site to the nearest 500 millimetres.

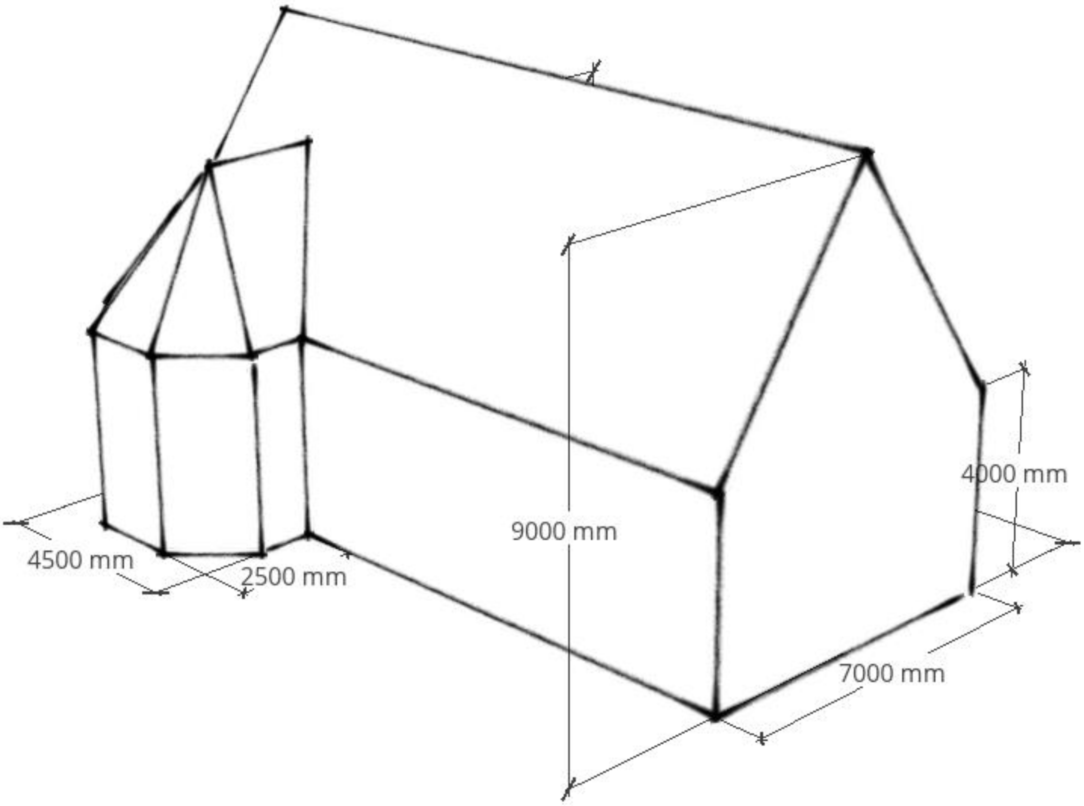


Figure 67: Ross Uniting Church – internal perspective view

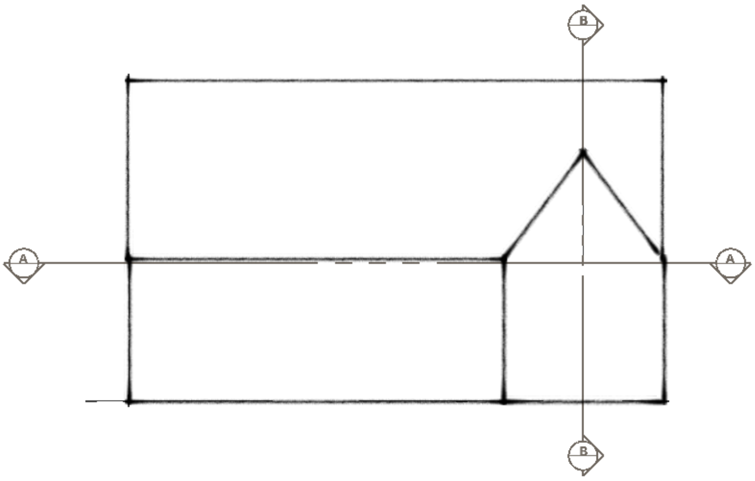


Figure 68: Ross Uniting Church – internal North elevation

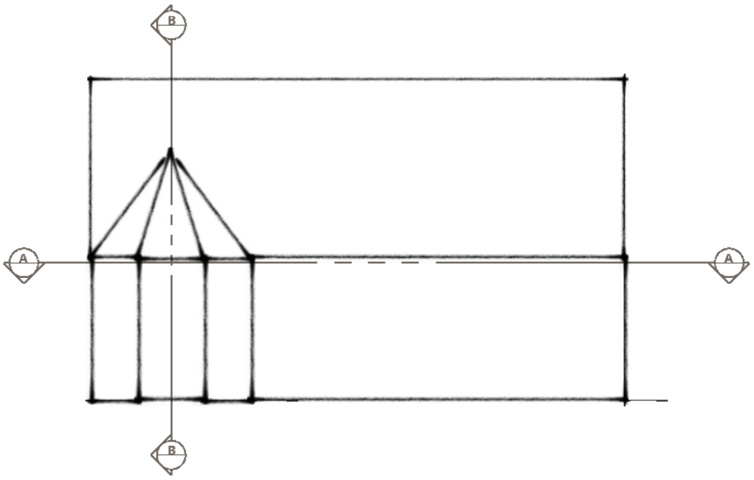


Figure 69: Ross Uniting Church – internal South elevation

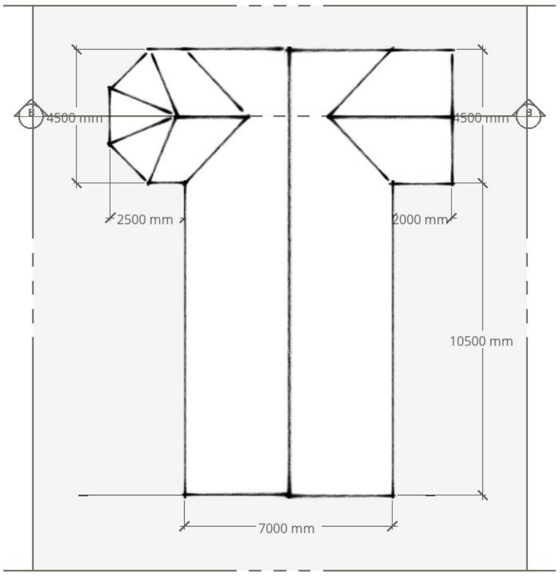


Figure 70: Ross Uniting Church – internal plan view

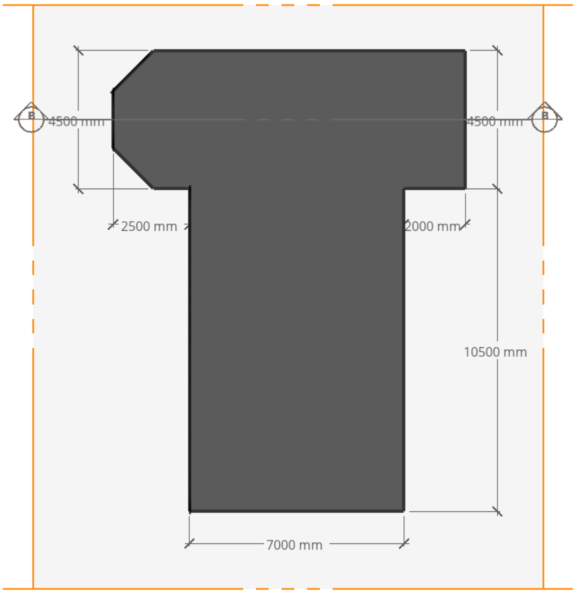


Figure 71: Ross Uniting Church – Section A

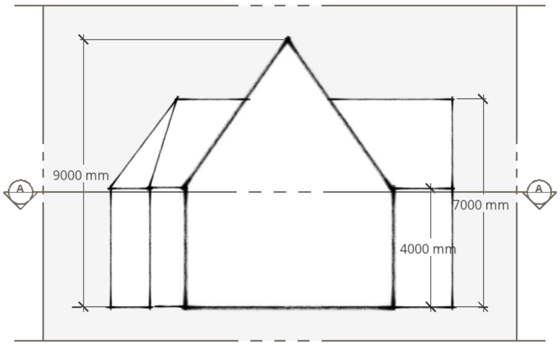


Figure 72: Ross Uniting Church – internal East elevation

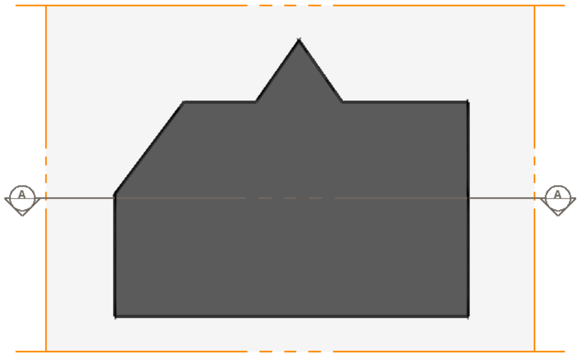


Figure 73: Ross Uniting Church – Section B

F5 Holy Trinity Anglican Church

Figure 74: Holy Trinity Anglican Church – interior of church facing chancel

Figure 75: Holy Trinity Anglican Church – interior of church facing nave (Photography: John Huth[11])

The following drawings are from the *Collection of the Queen Victoria Museum and Art Gallery, Launceston, Tasmania* QVM AD series[12], and have been reproduced with permission.

---

[11] Holy Trinity Anglican Church churchesaustralia.org/list-of-churches/locations/tasmania/directory/1145-holy-trinity-anglican-church

[12] QVMAG Library *Architectural and engineering drawings and maps* qvmag.tas.gov.au/Collections/Library-and-Archives/The-Librarys-Collections/Maps-architectural-and-engineering-drawings

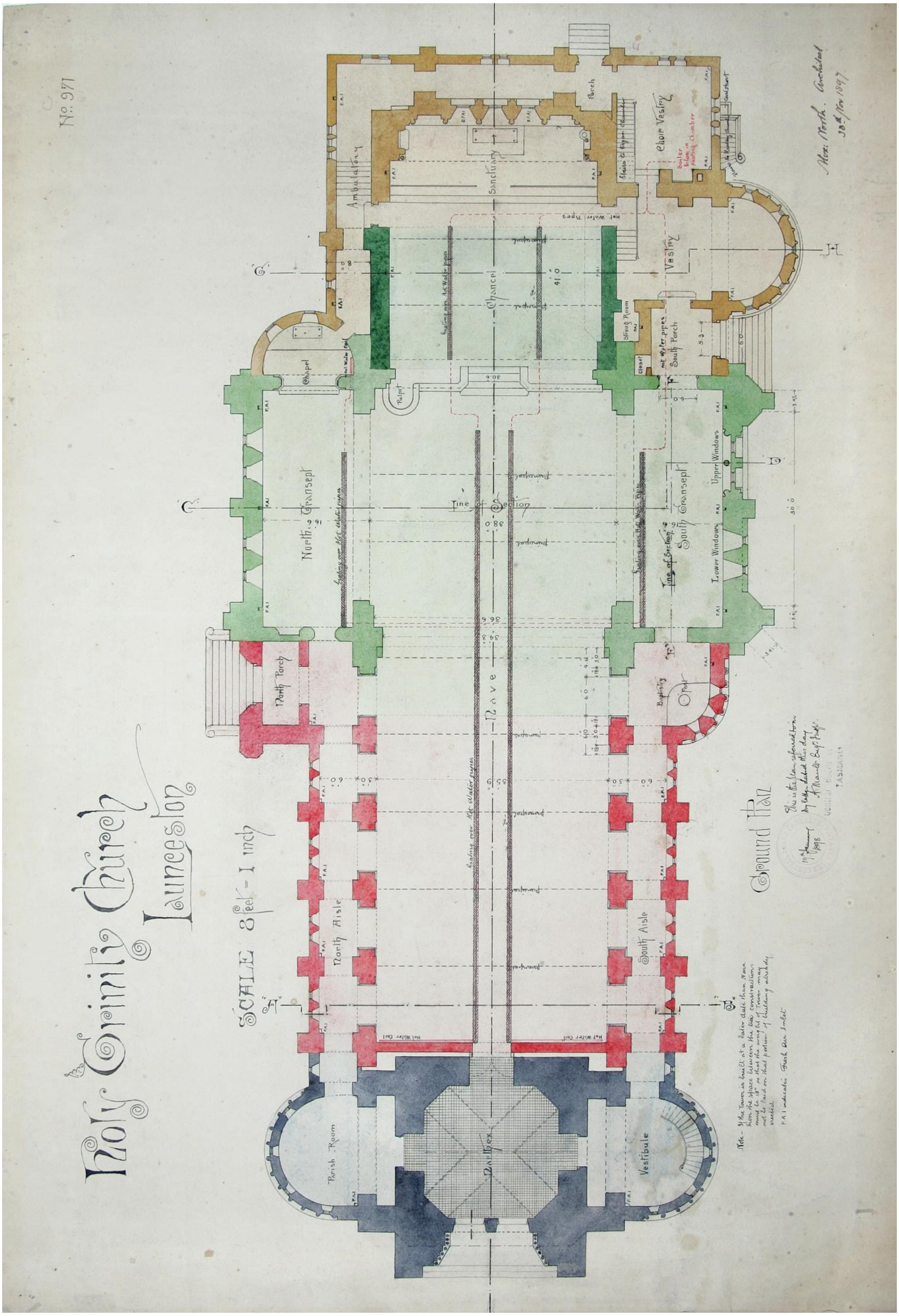


Figure 76: Holy Trinity Anglican Church – Ground Plan

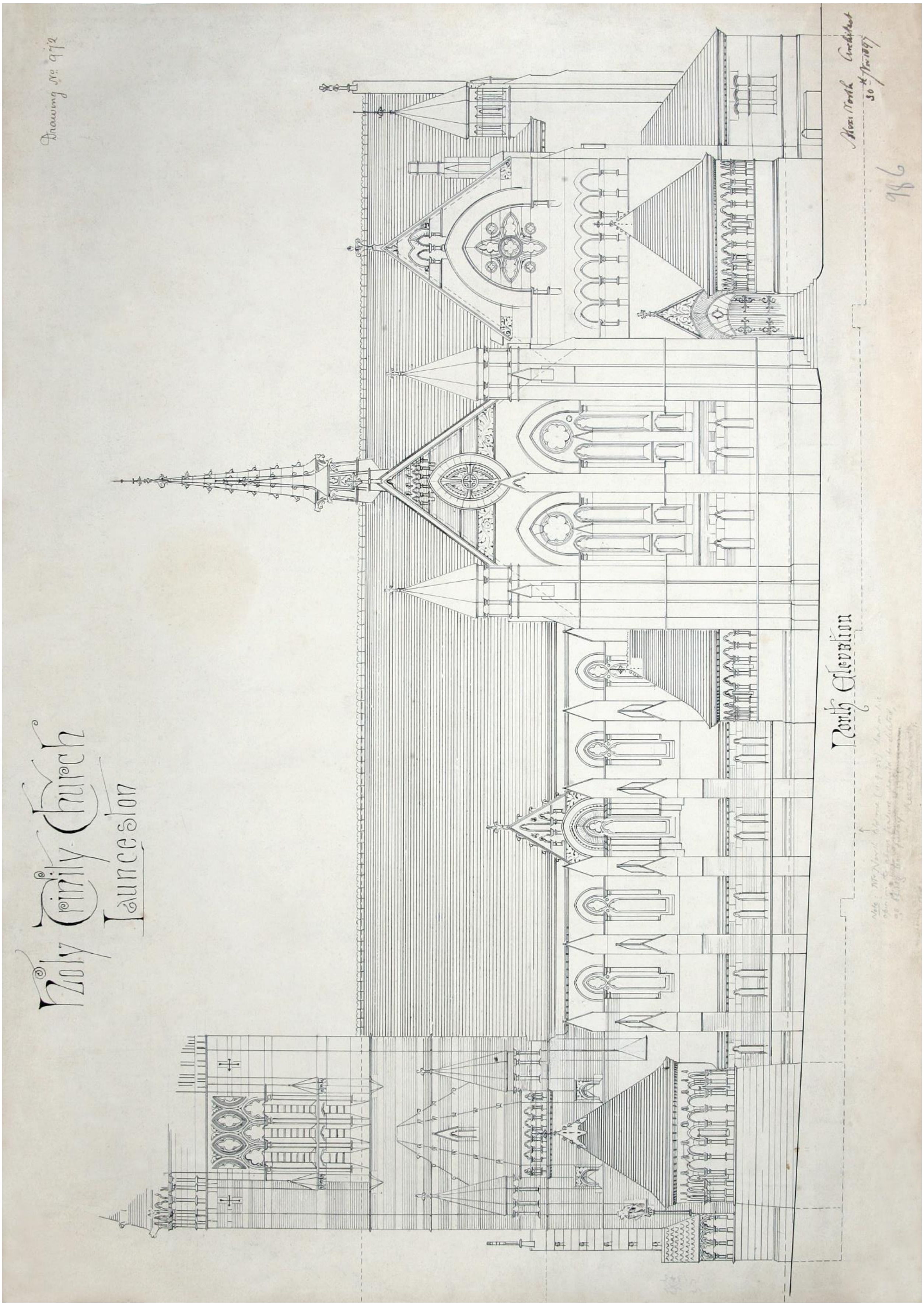


Figure 77: Holy Trinity Anglican Church – North Elevation

The following drawing has been provided by Holy Trinity Anglican Church.

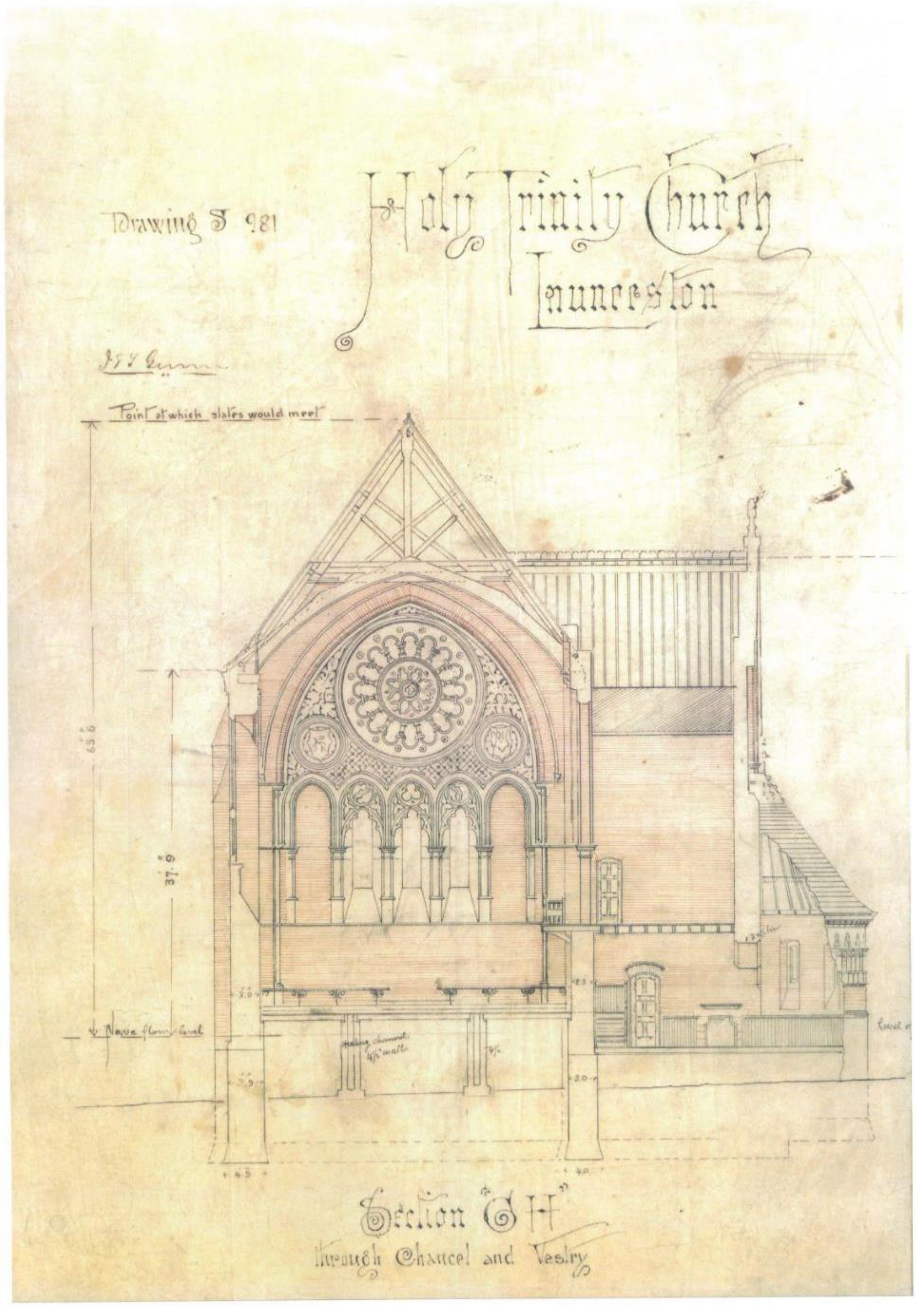


Figure 78: Holy Trinity Anglican Church – Section through Chancel and Vestry

F6 St Paul’s Cathedral

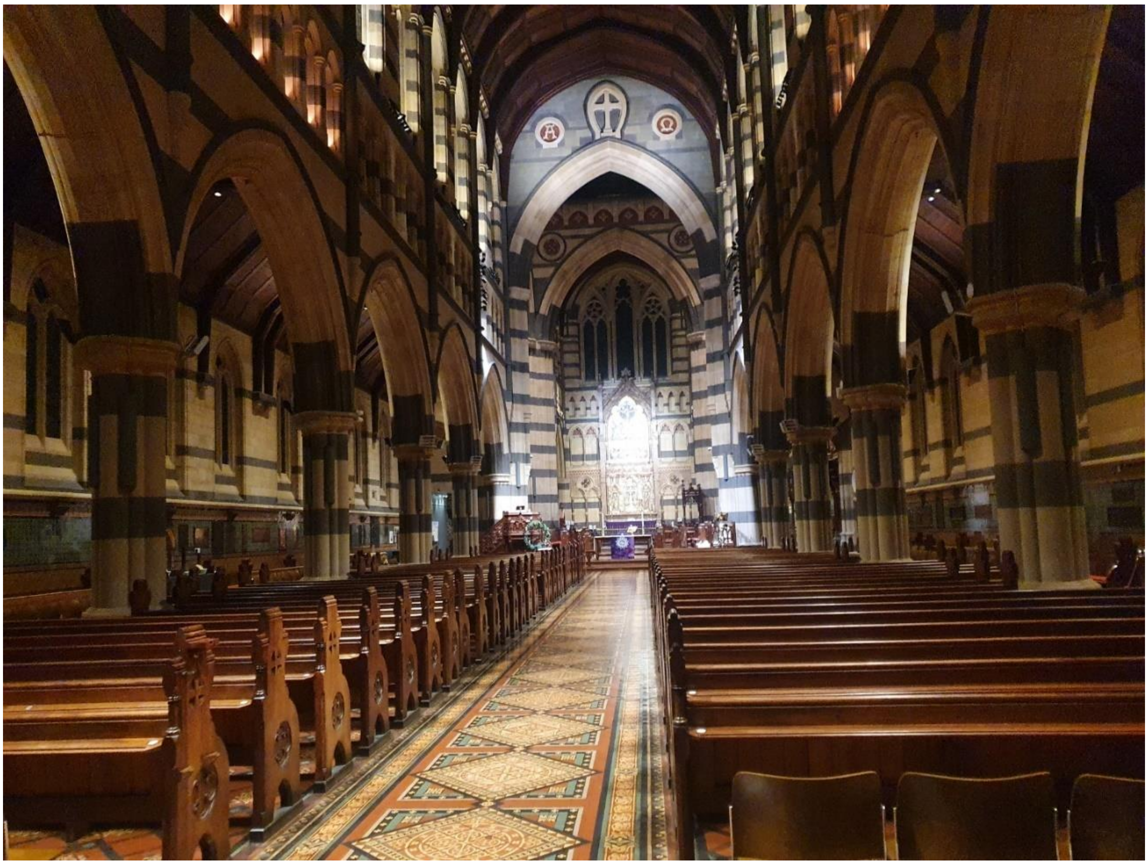


Figure 79: St Paul’s Cathedral – interior of church facing chancel

Figure 80: St Paul’s Cathedral – interior of church facing nave

The following drawing has been provided by St Paul’s Cathedral.

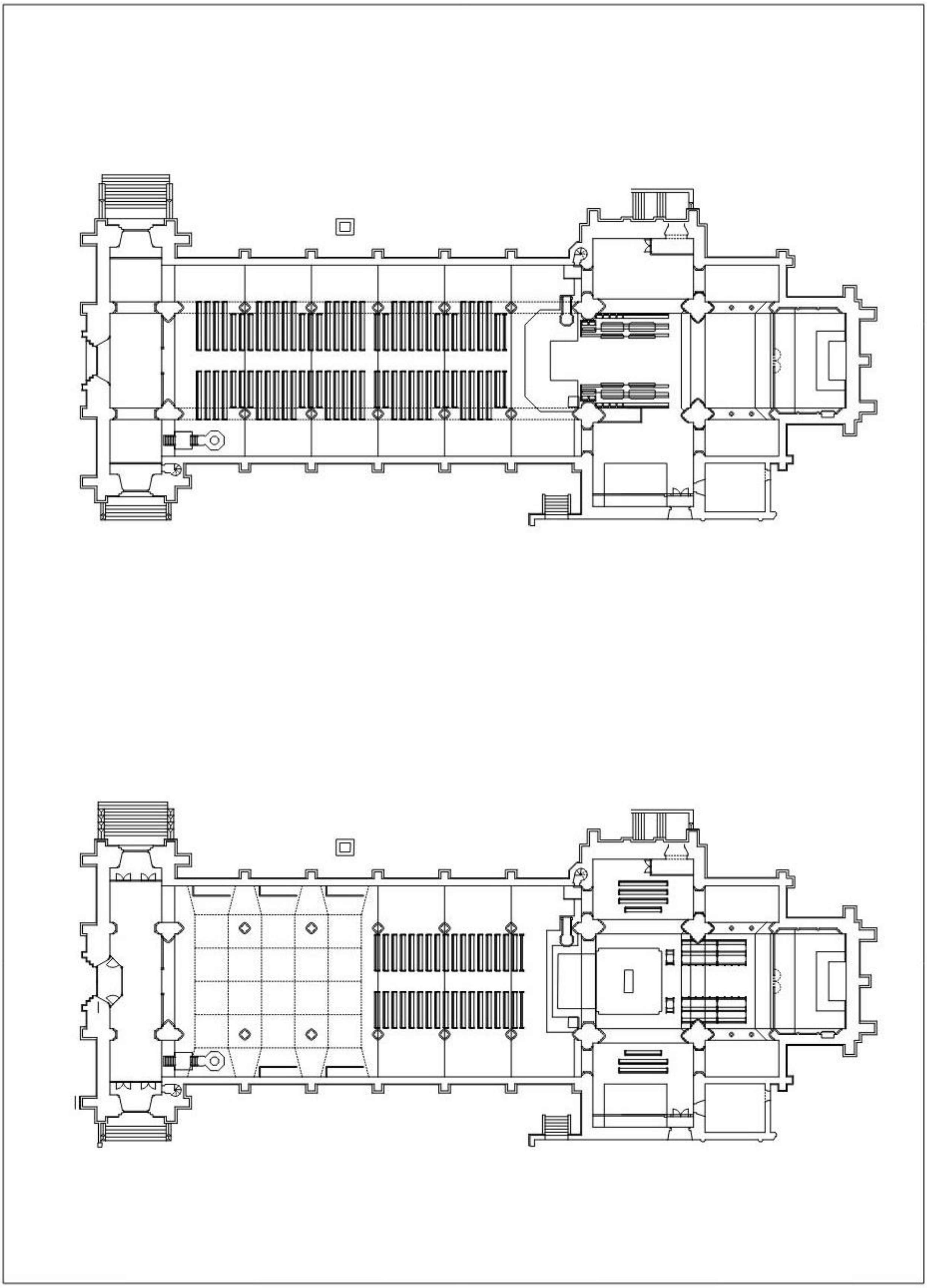


Figure 81: St Paul’s Cathedral – Floor Plans

The following drawings have been prepared by Falkinger Adronas and provided by St Paul's Cathedral.

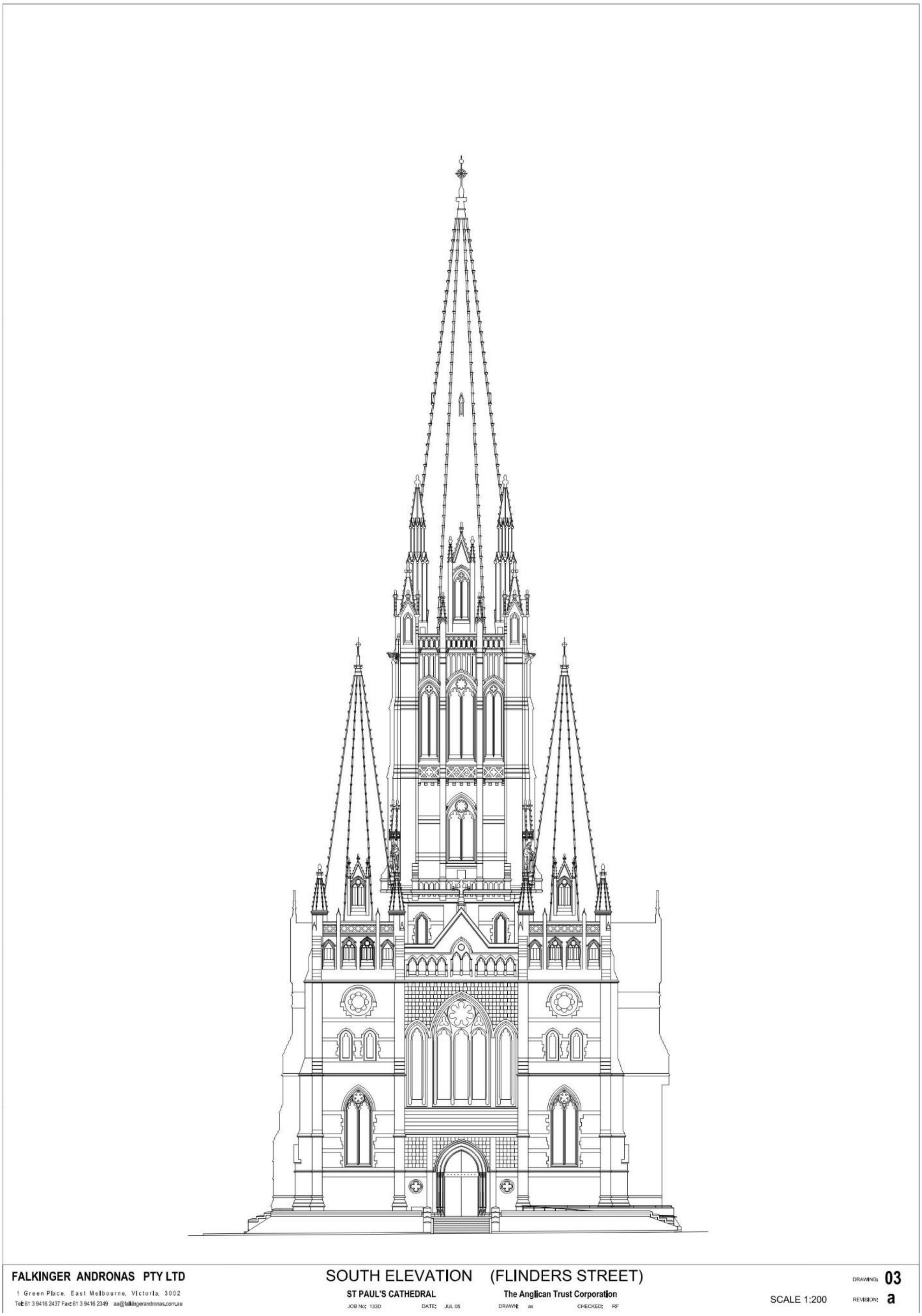


Figure 82: St Paul's Cathedral – South Elevation

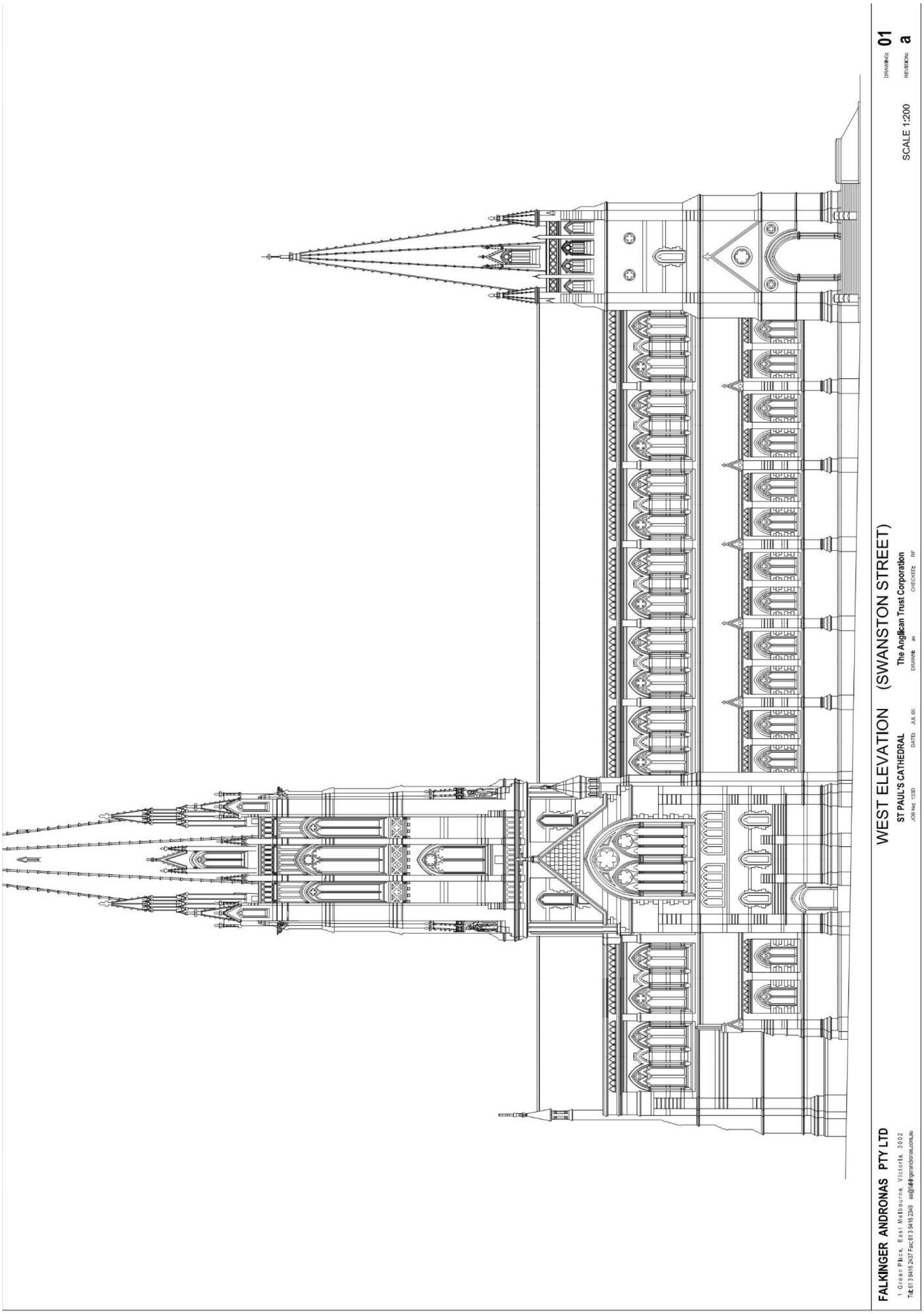


Figure 83: St Paul's Cathedral – West Elevation

F7 Ian Roach Hall, Scotch College

Figure 84: Ian Roach Hall – interior of auditorium facing the stage
(Source: Yasmin Rowe yasminrowe.com/events/solo-concerto/)

The architectural drawings for Ian Roach Hall could not be obtained.

F8 Dorothy Pizzey Centre, St Catherine's School

Figure 85: Dorothy Pizzey Centre – interior of hall facing stage

Figure 86: Dorothy Pizzey Centre – interior of hall facing audience seating

The following drawings have been prepared by Croxon Ramsay and provided by St Catherine's School.

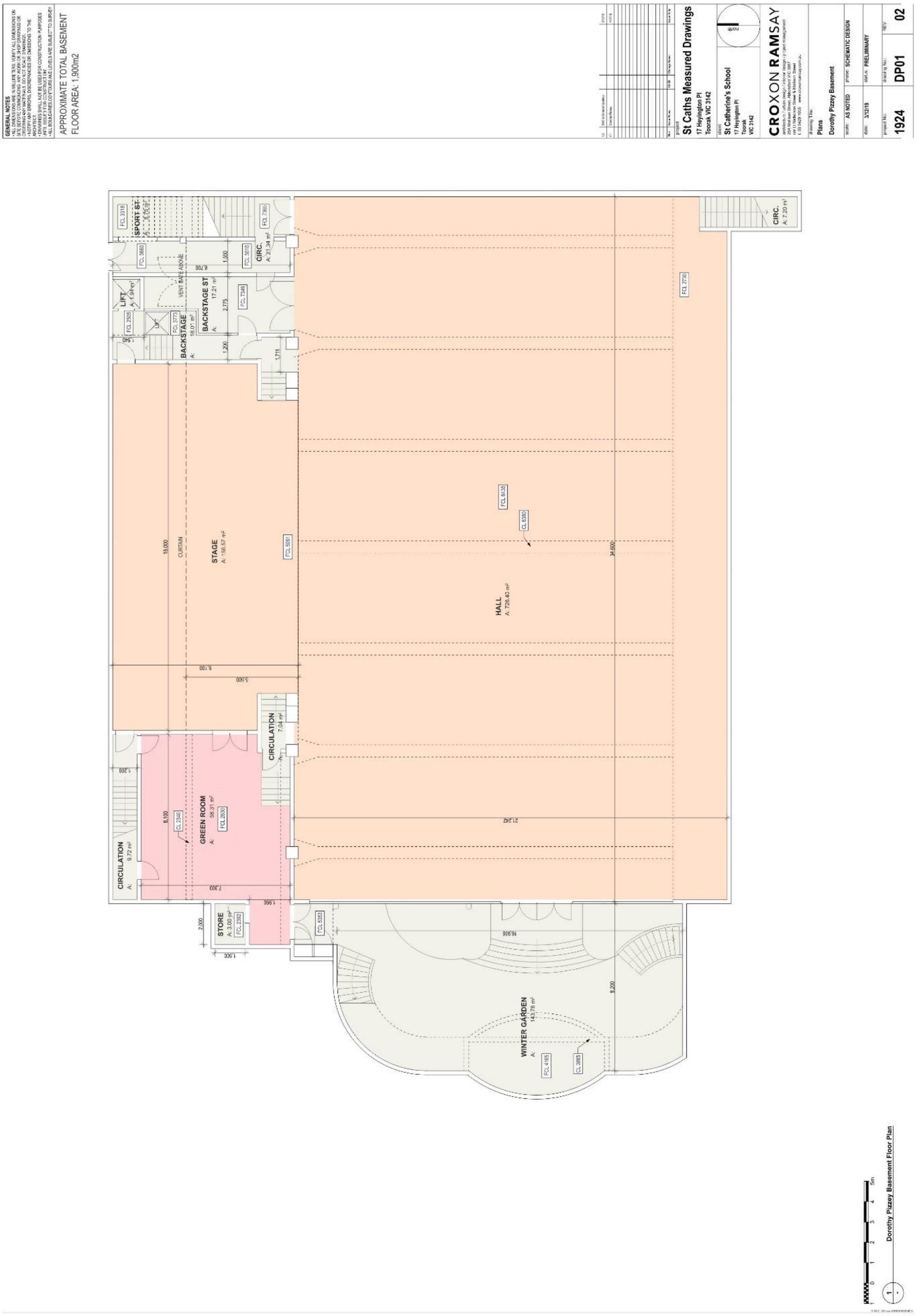


Figure 87: Dorothy Pizzey Centre – Basement Plan

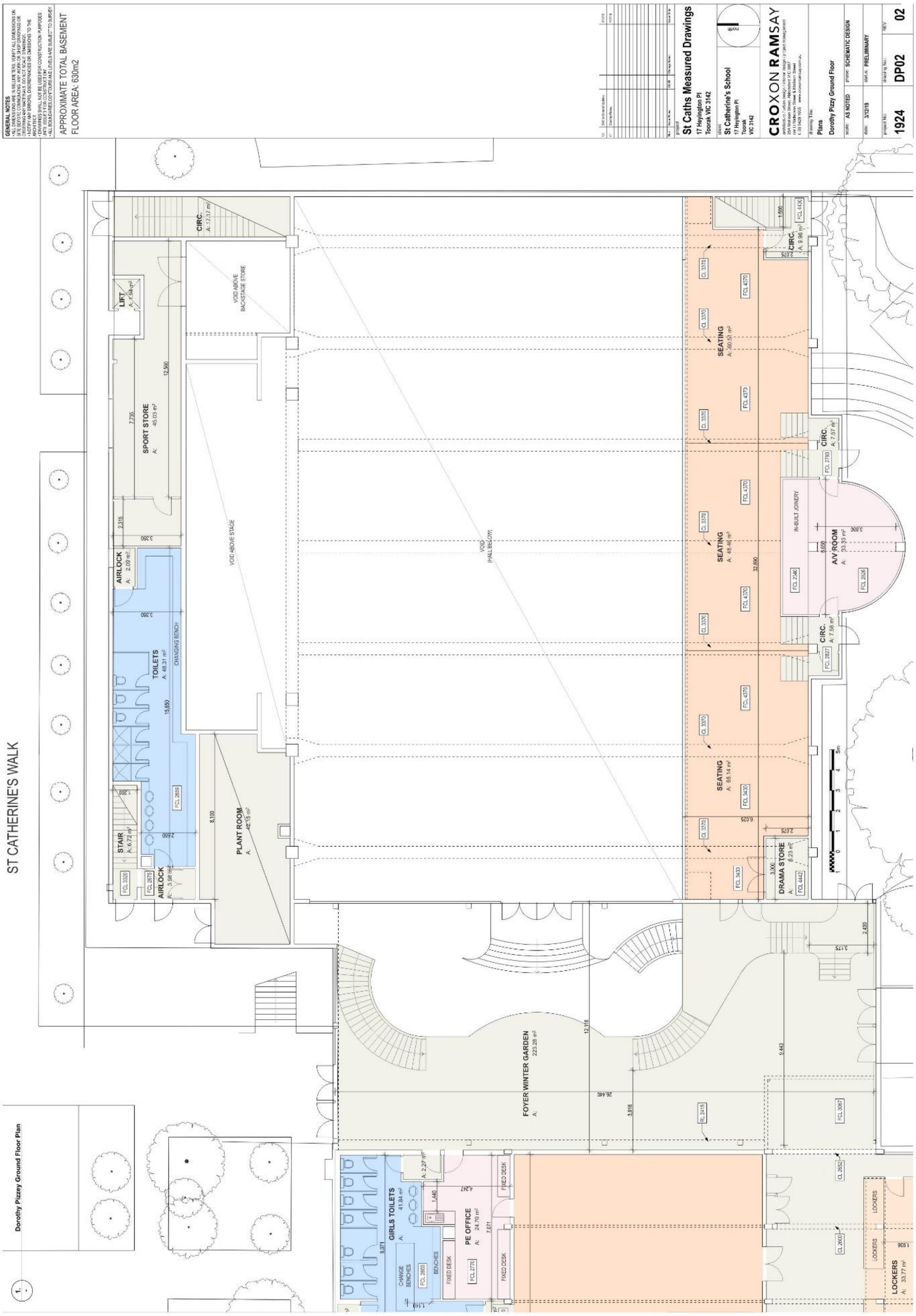


Figure 88: Dorothy Pizzey Centre – Ground Floor Plan

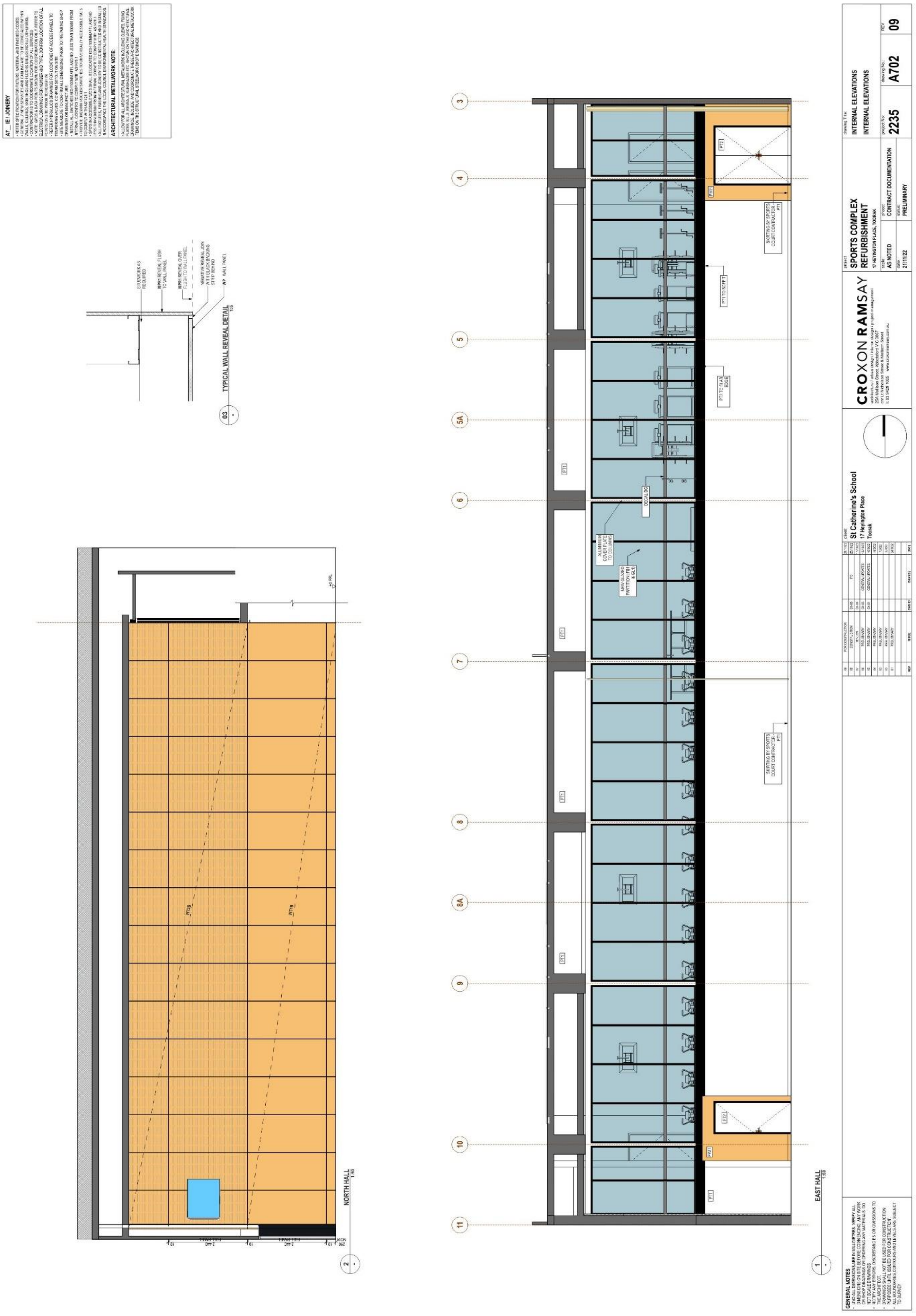


Figure 89: Dorothy Pizzey Centre – Internal Elevations 1

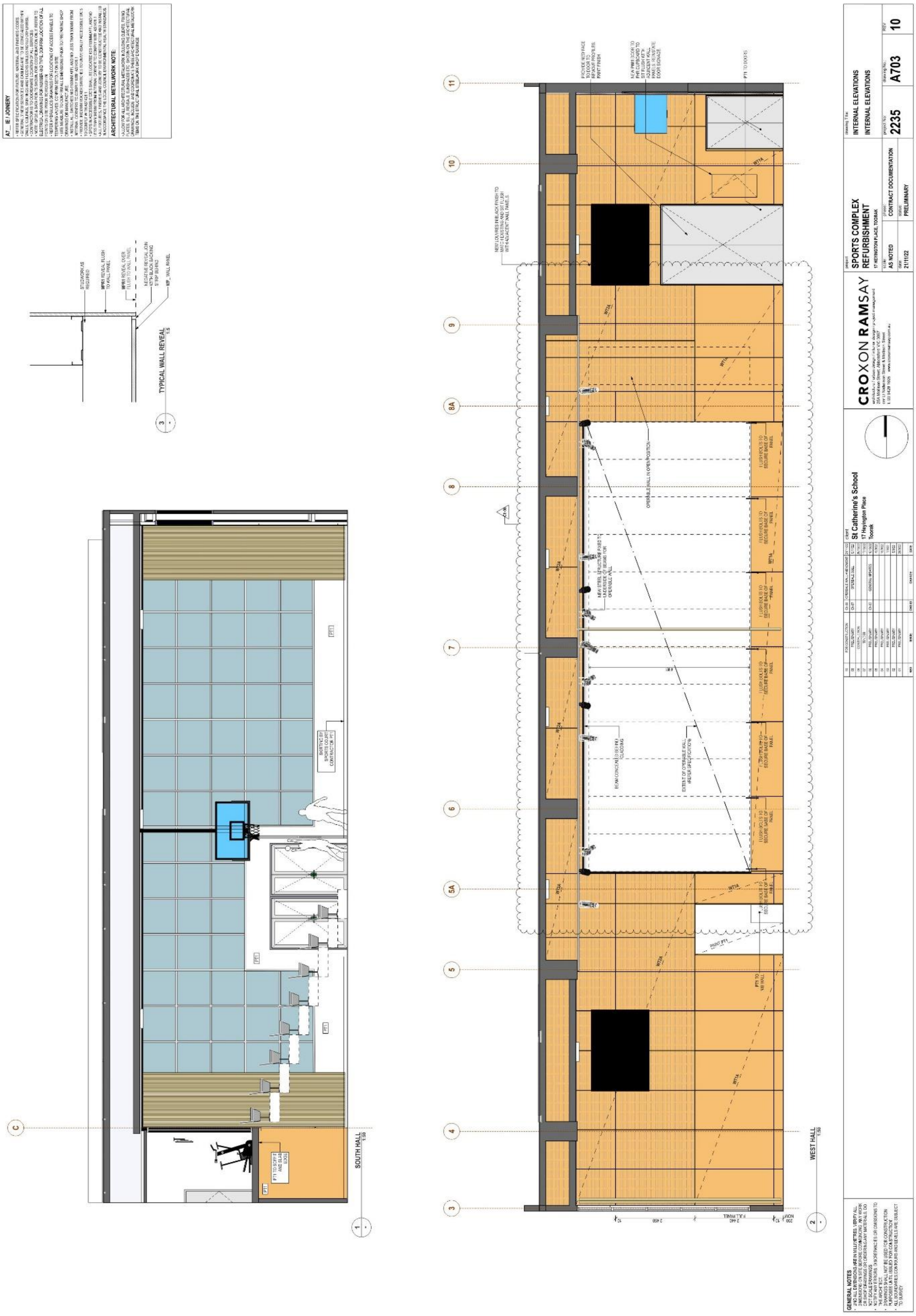


Figure 90: Dorothy Pizzey Centre – Internal Elevations 2

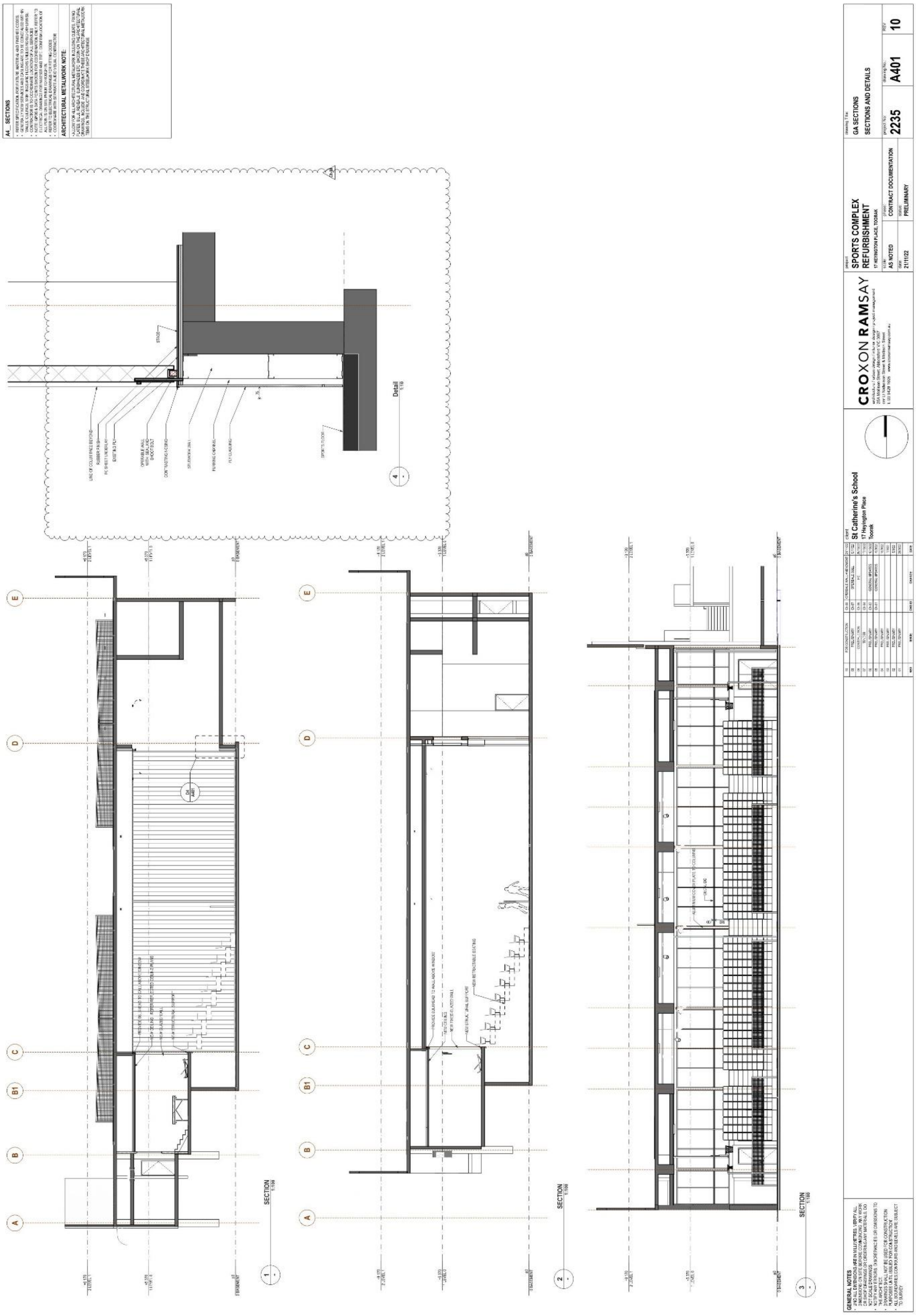


Figure 91: Dorothy Pizzey Centre – Sections and Details

F9 Christ Church St Laurence

Figure 92: Christ Church St Laurence – interior of church facing chancel

Figure 93: Christ Church St Laurence – interior of church facing nave

The following drawings have been prepared by Paul Davies and provided by Christ Church St Laurence.

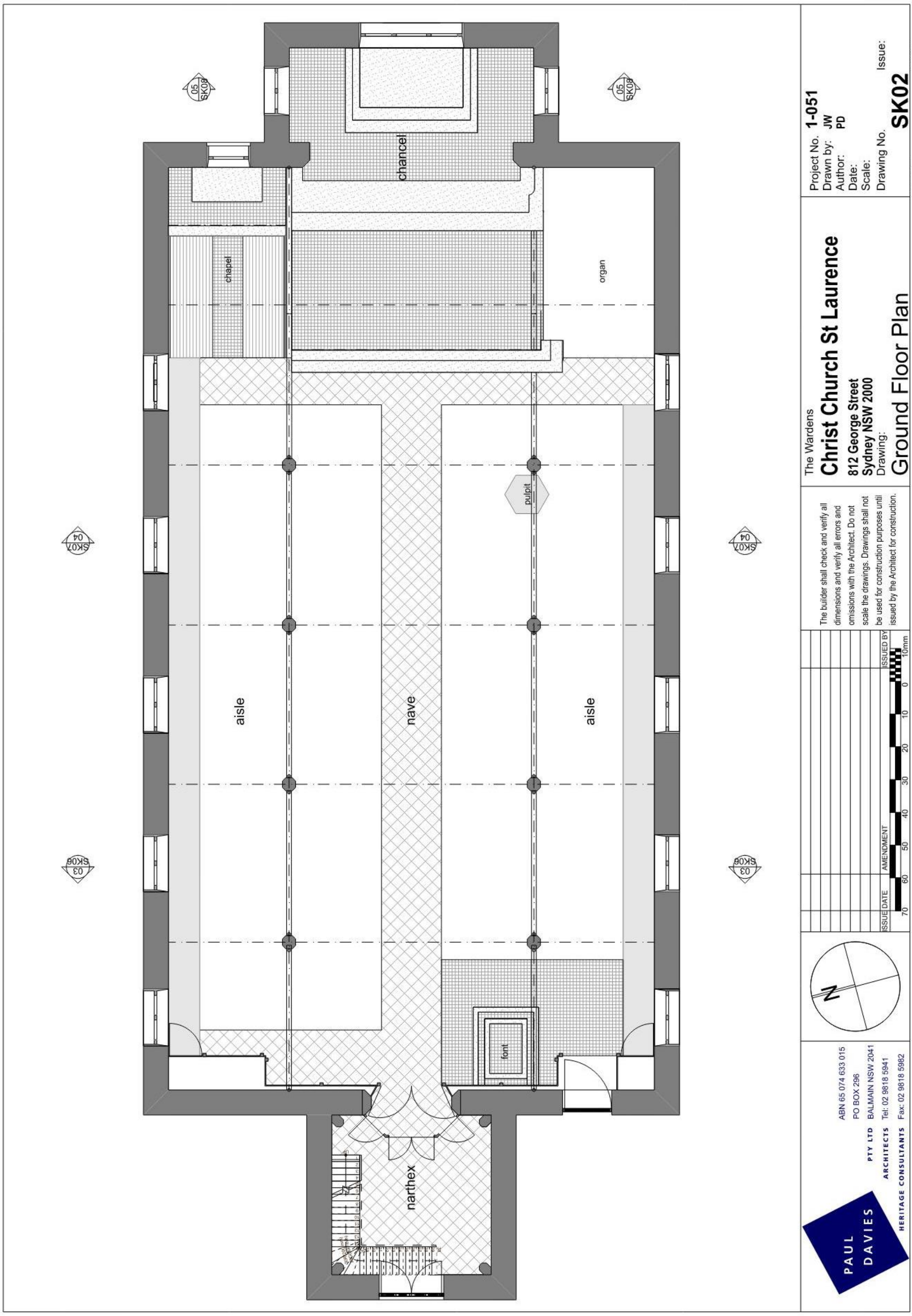


Figure 94: Christ Church St Laurence – Ground Floor Plan

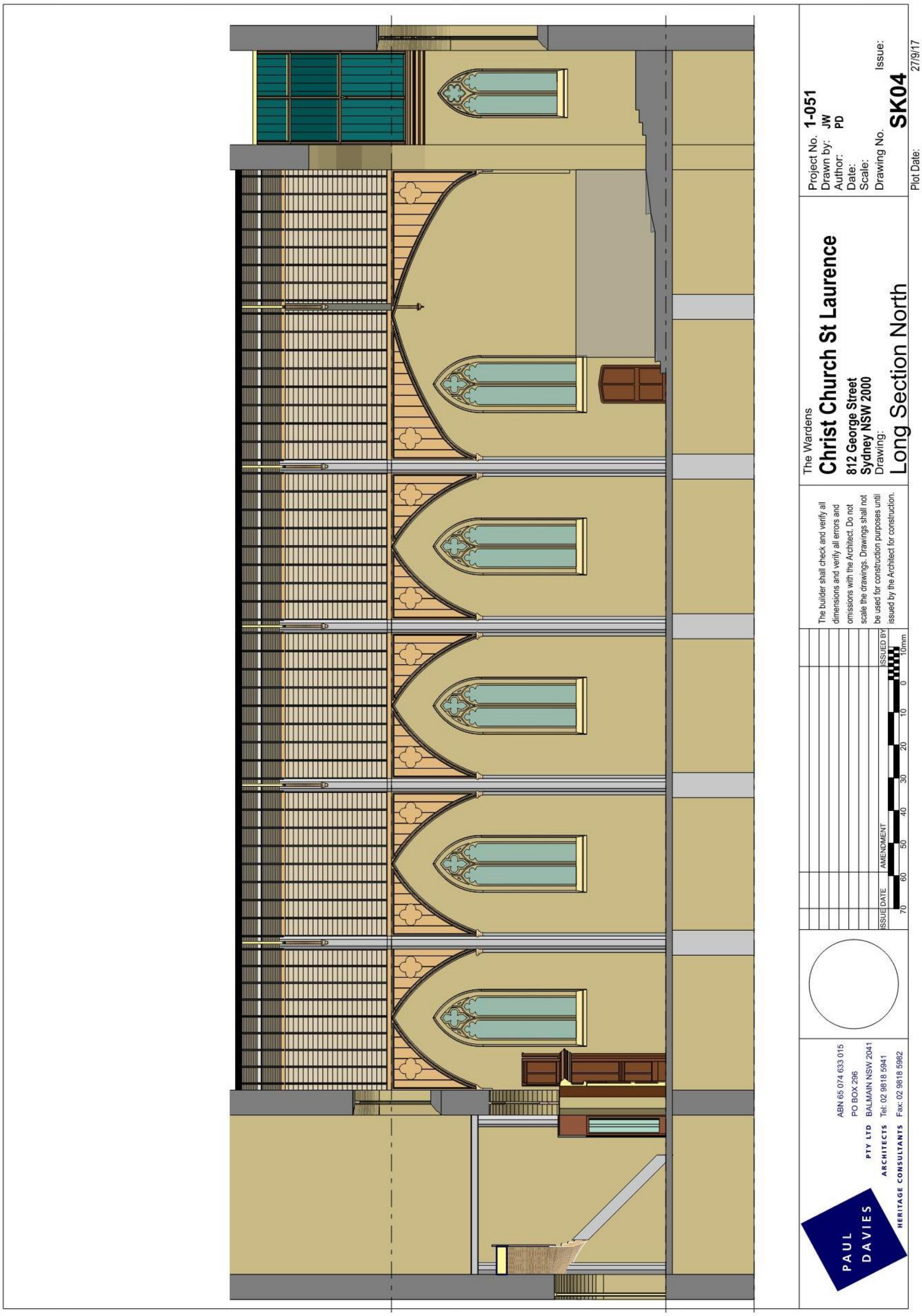


Figure 95: Christ Church St Laurence – Long Section North

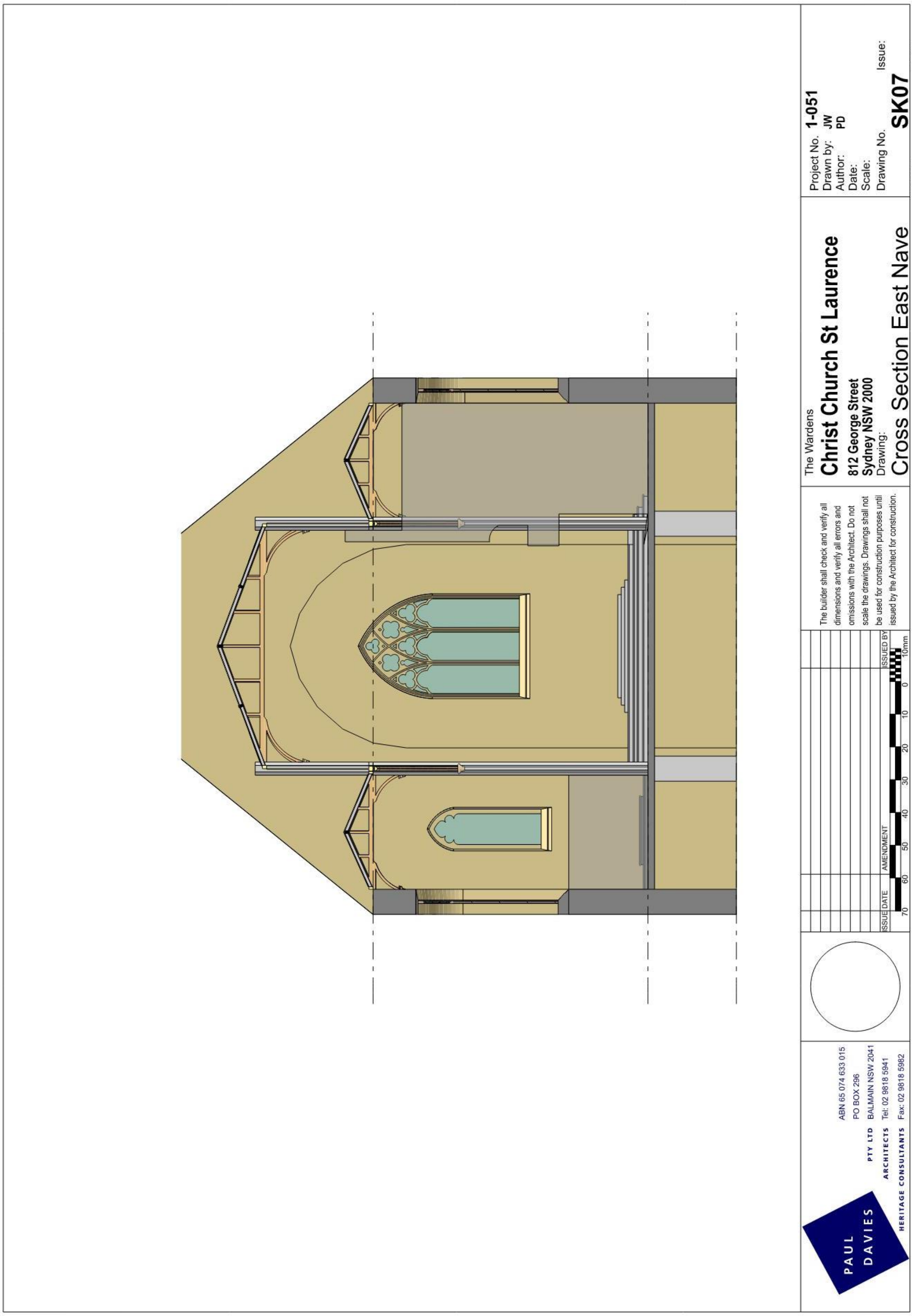


Figure 96: Christ Church St Laurence – Cross Section East Nave

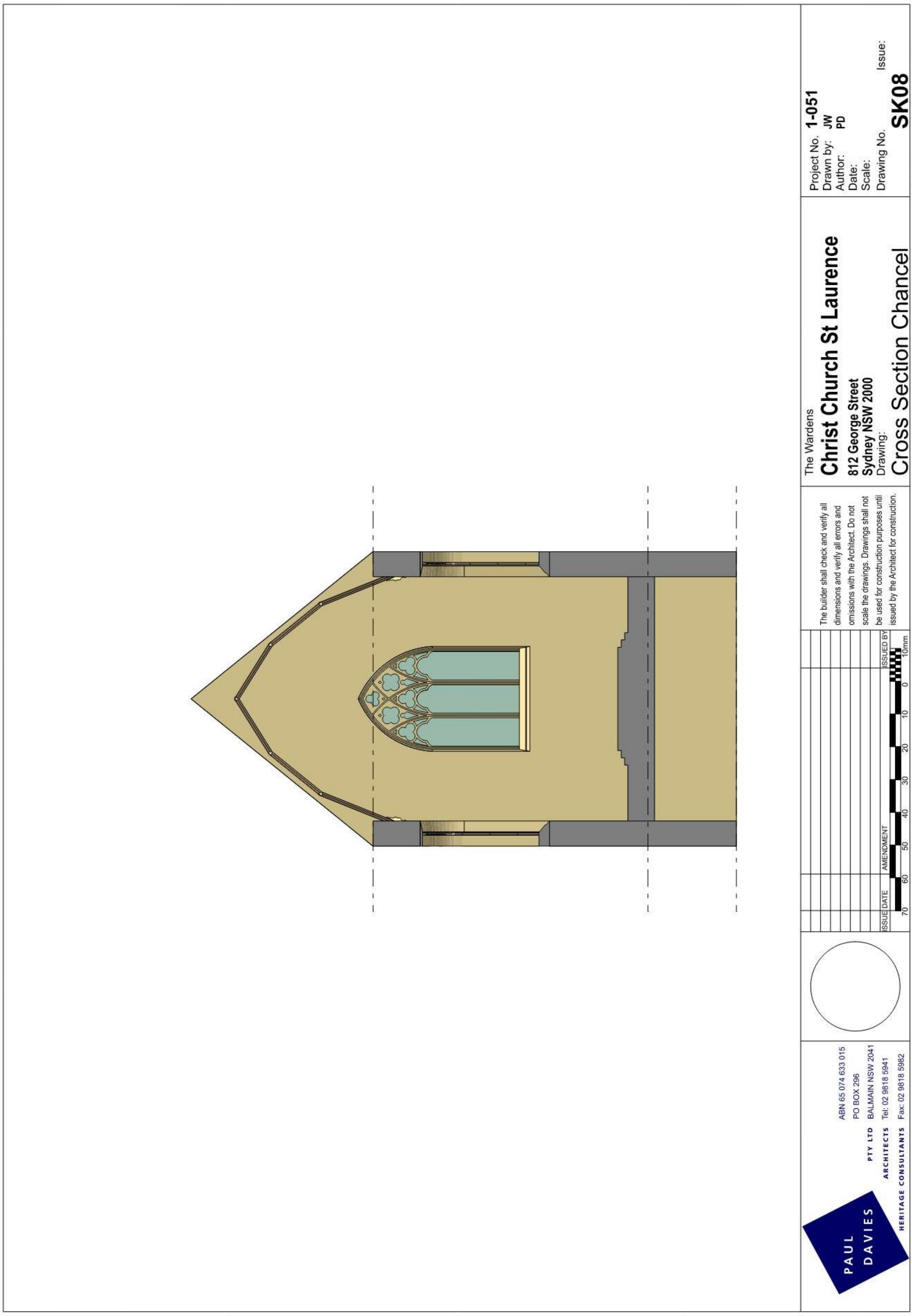


Figure 97: Christ Church St Laurence – Cross Section Chancel

F10 Sydney Opera House, Concert Hall

Figure 98: Sydney Opera House – Interior of Concert Hall facing the stage (Photography: Daniel Boud[13])

Figure 99: Sydney Opera House – Concert Hall stage with new overhead reflectors (Photography: Daniel Boud[13])

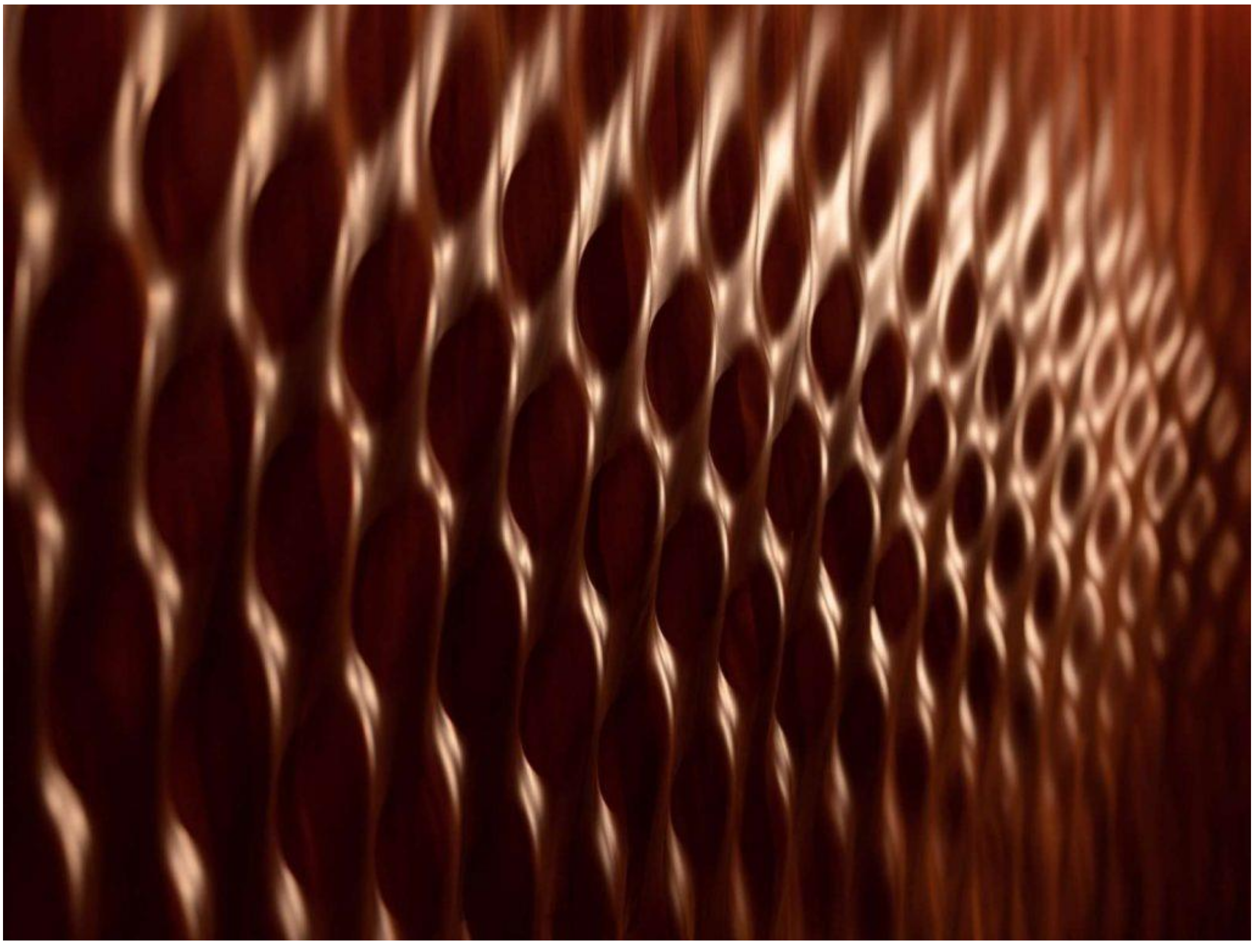


Figure 100: Sydney Opera House – Concert Hall profiled timber diffusers on side stage (Photography: Daniel Boud[13])

The current seating plan may be found on the Sydney Opera House's website[14]. The capacity is:

- Up to 2664 in the round
- Up to 2102 facing the stage

The following drawings have been reproduced from the 'Red Book,' which was presented by architect Jørn Utzon in 1958 to the Premier and the Sydney Opera House Committee [42]. The report includes architectural drawings of the original design and contains input from other consultants including Vilhelm Lassen Jordan on acoustics.

The book has been accessed online through the *Museums of History NSW - State Archives Collection*[15]. The series is out of copyright protection.

---

[13] The Spaces – Sydney Opera House emerges with a whole new sound thanks to an acoustic refit thespaces.com/sydney-opera-house-emerges-with-a-whole-new-sound-thanks-to-an-acoustic-refit/

[14] Sydney Opera House – Concert Hall sydneyoperahouse.com/hire-a-venue/stage-a-performance/venues/concert-hall

[15] Museums of History NSW - State Archives Collection: Department of Public Works; NRS NRS-12707, "Sydney National Opera House" ("Red Book"), 1958. mhnsw.au/stories/general/sydney-opera-house-the-red-book/

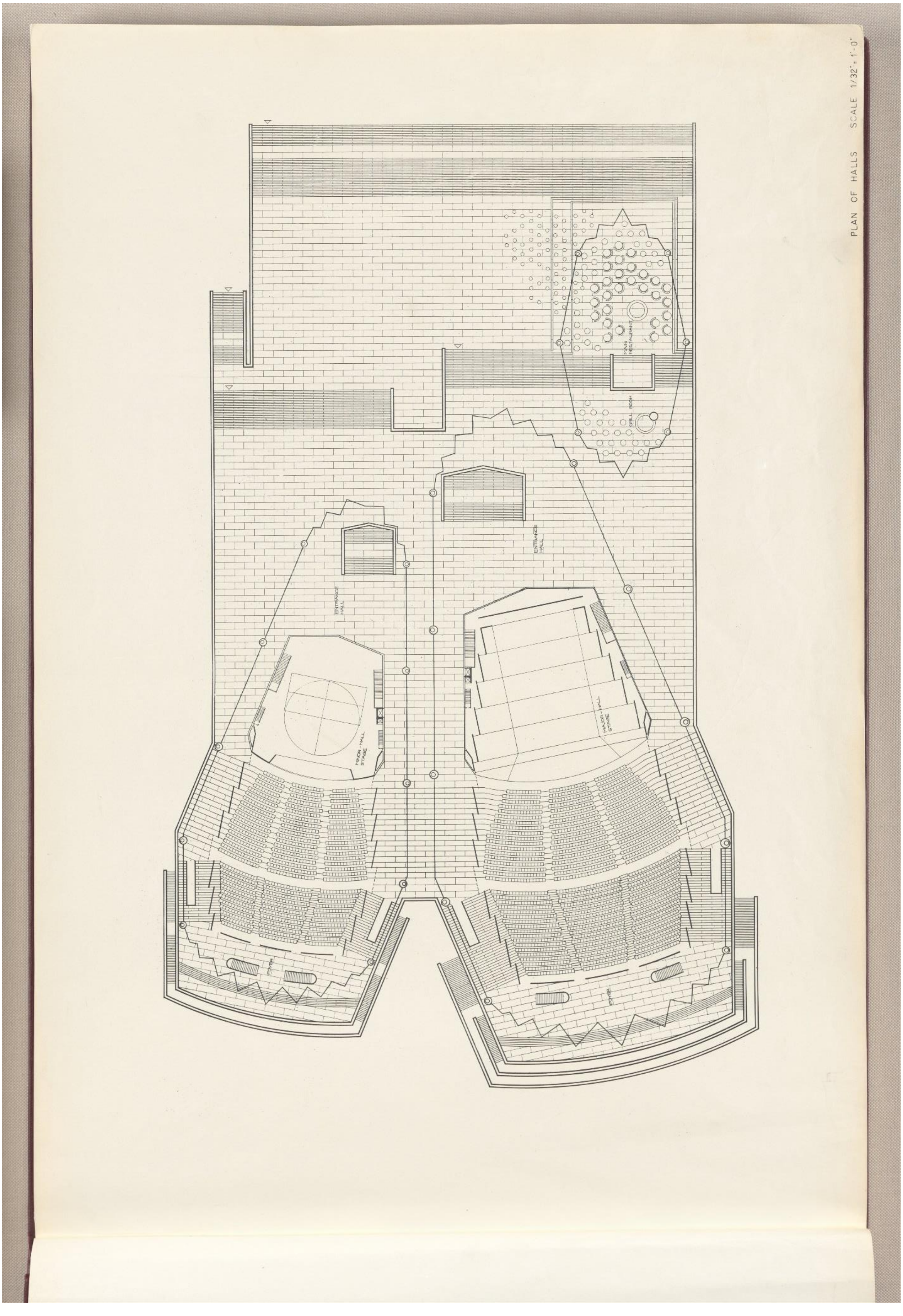


Figure 101: Sydney Opera House – Plan of Halls

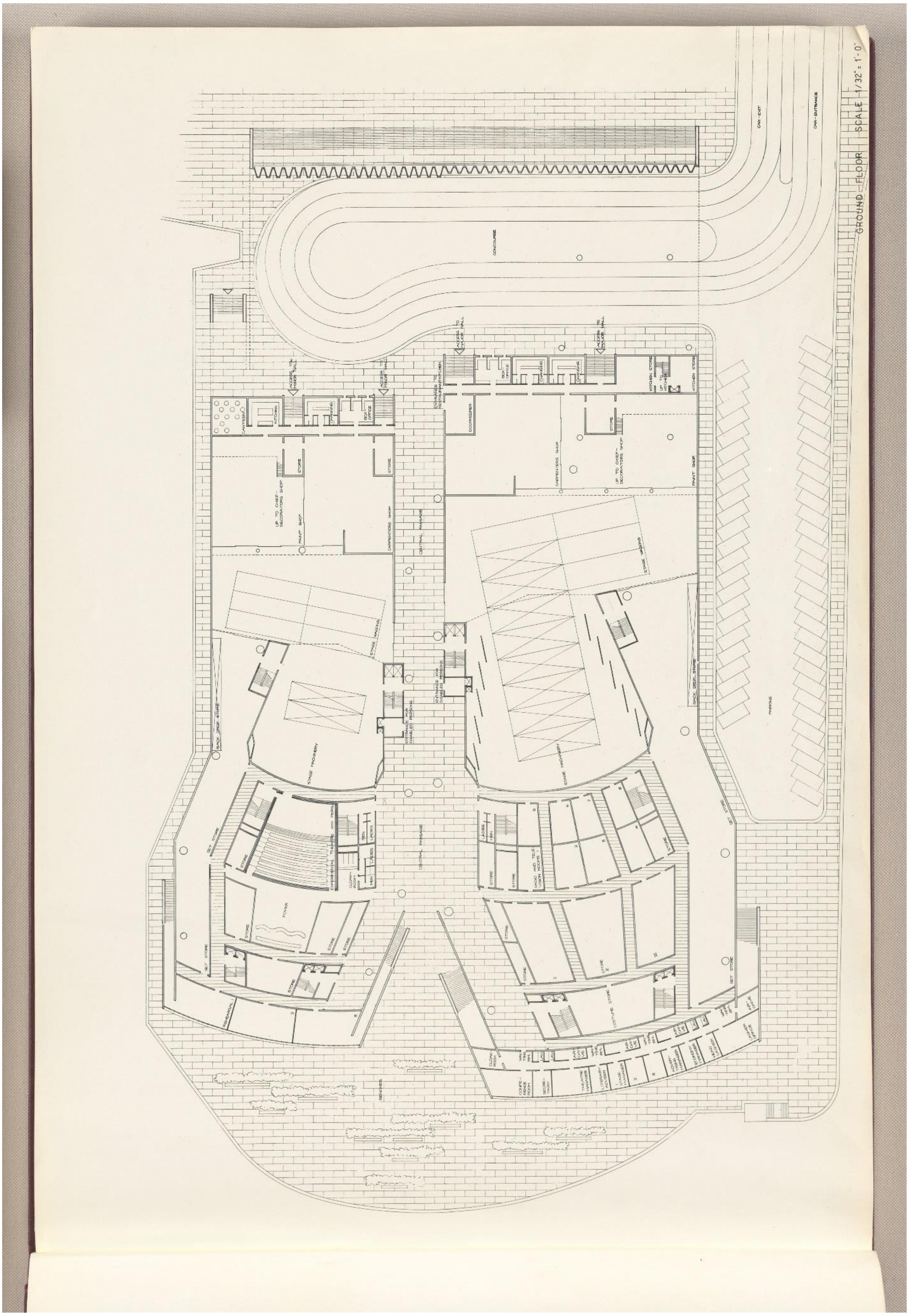


Figure 102: Sydney Opera House – Ground Floor

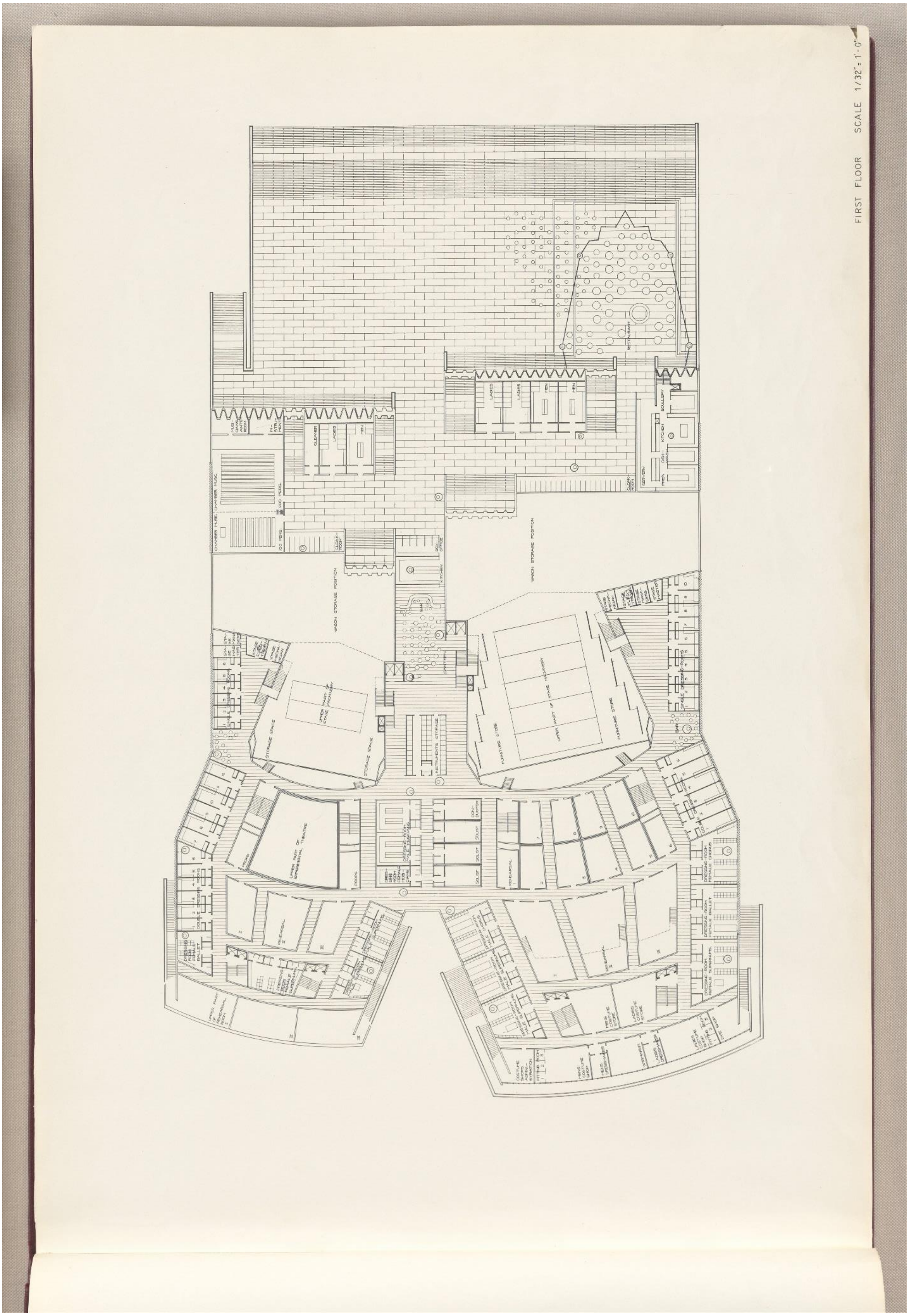


Figure 103: Sydney Opera House – First Floor

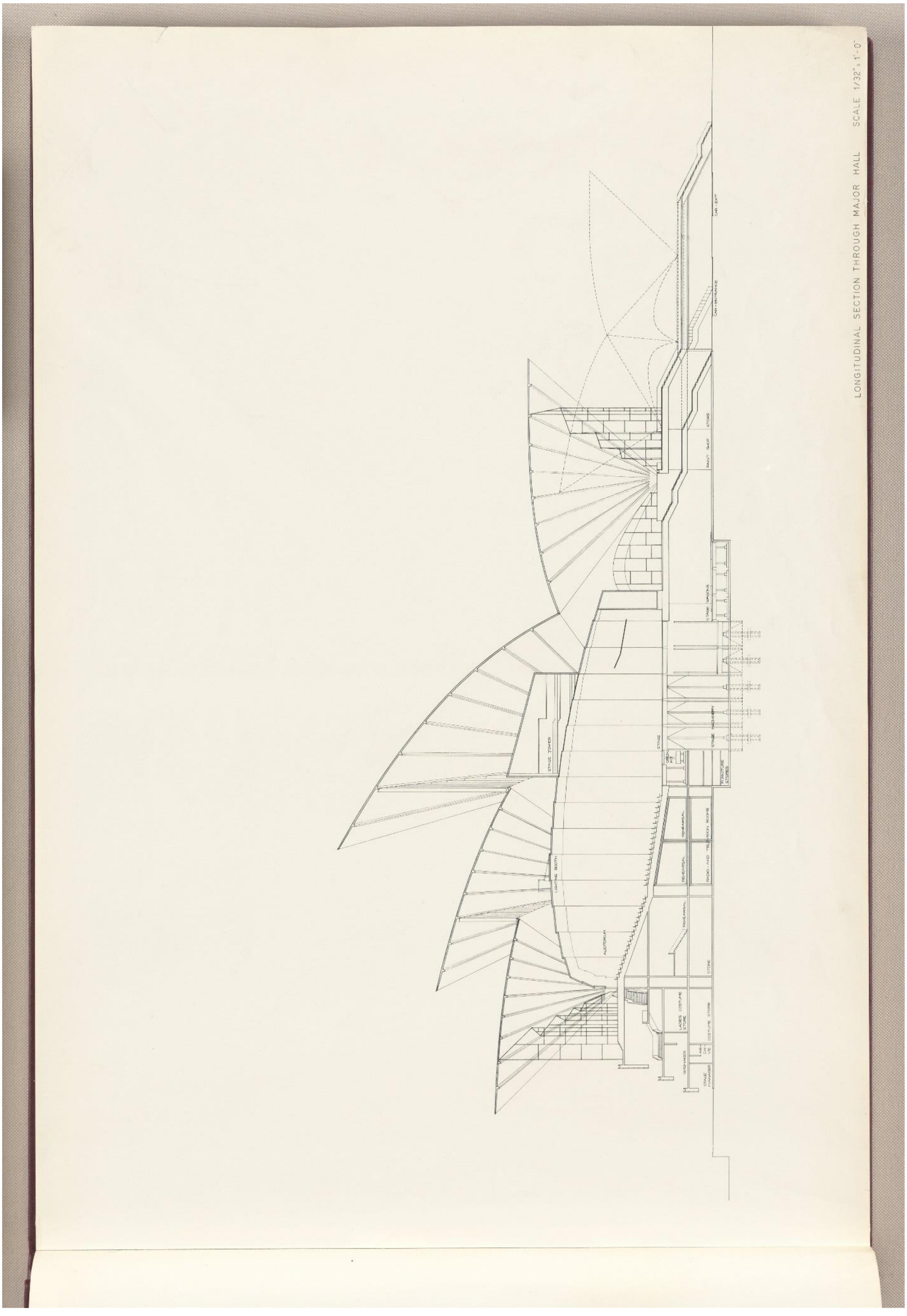


Figure 104: Sydney Opera House – Longitudinal Section through Major Hall

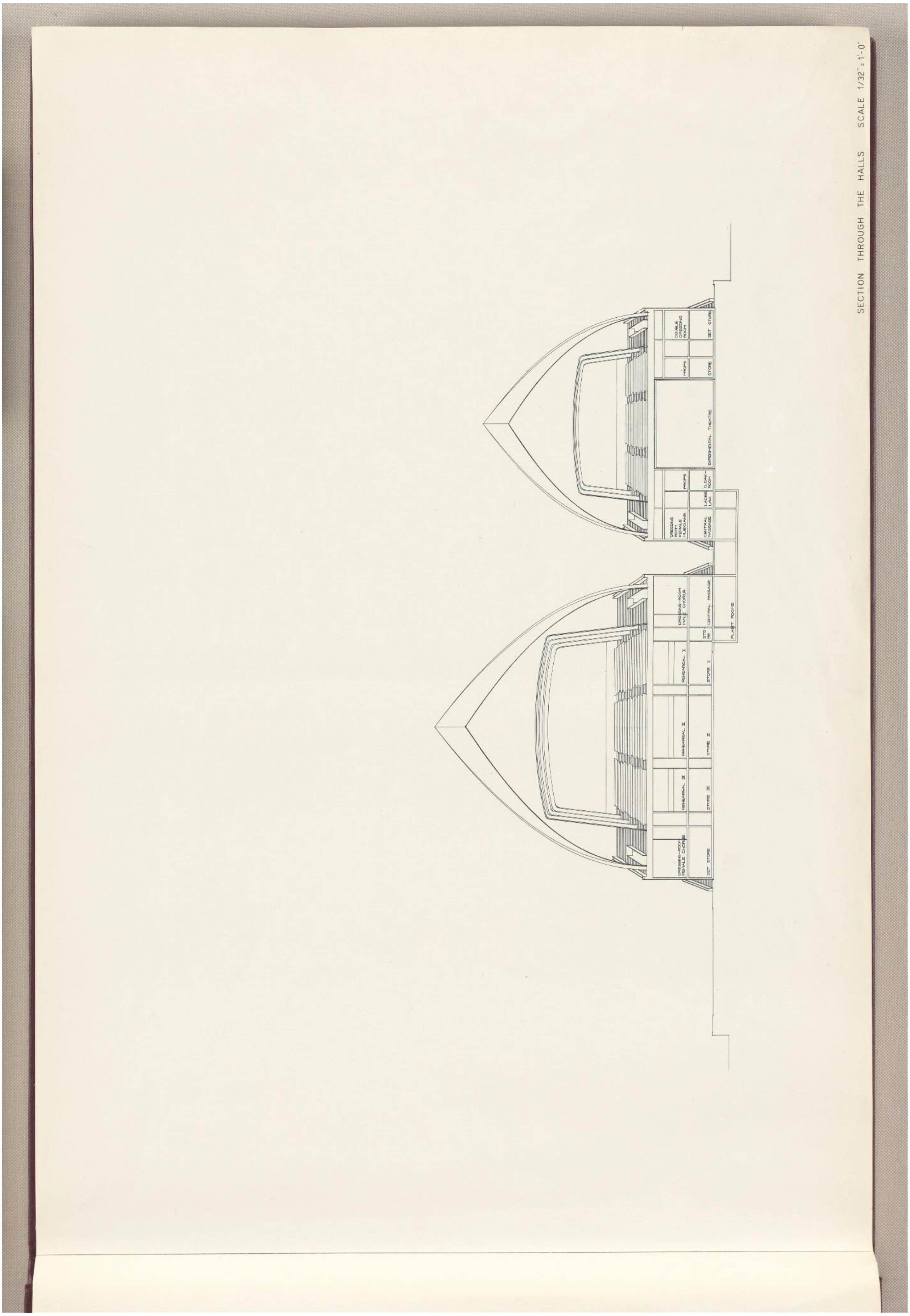


Figure 105: Sydney Opera House – Section through the Halls

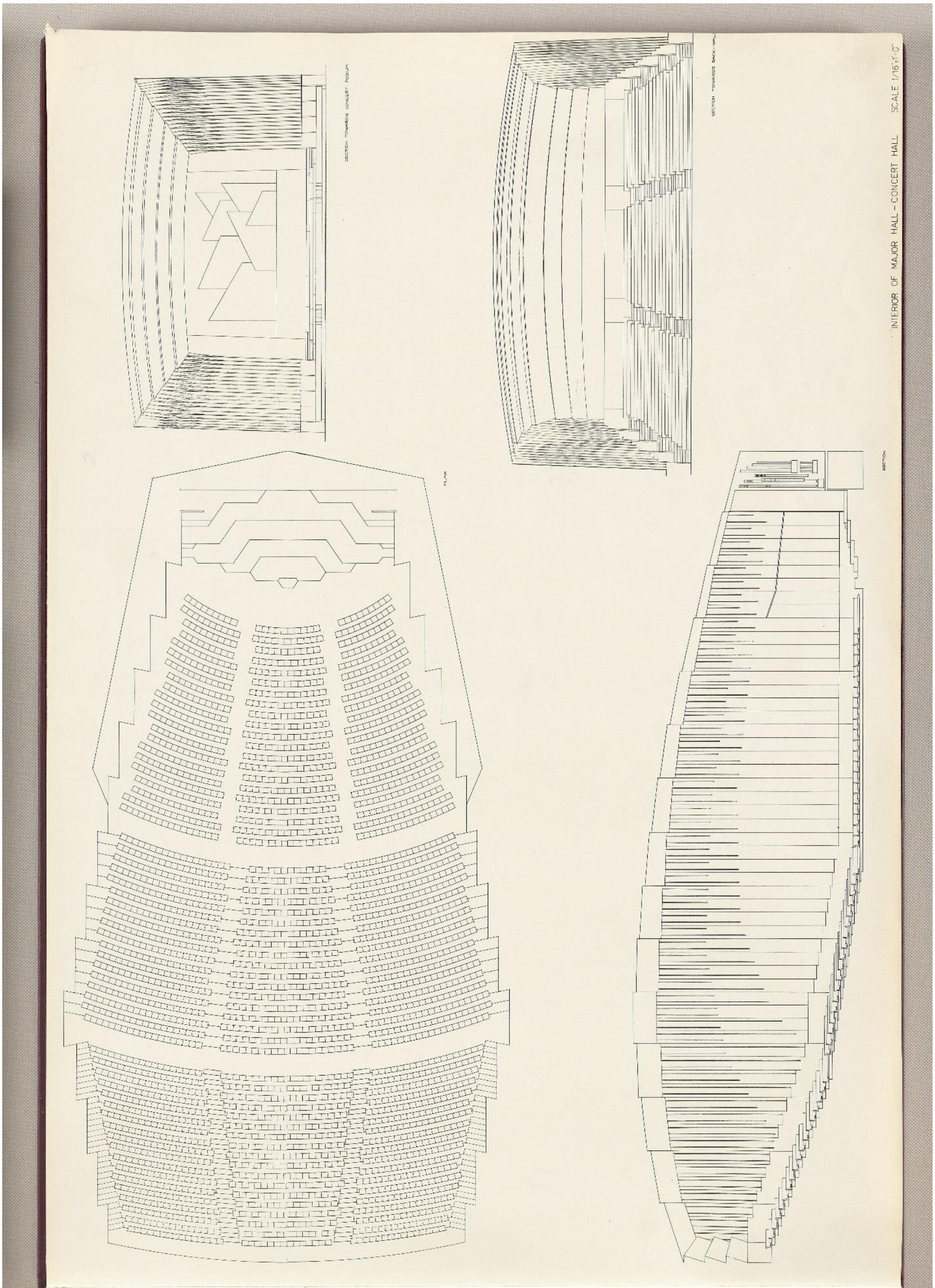


Figure 106: Sydney Opera House – Interior of Major Hall - Concert Hall

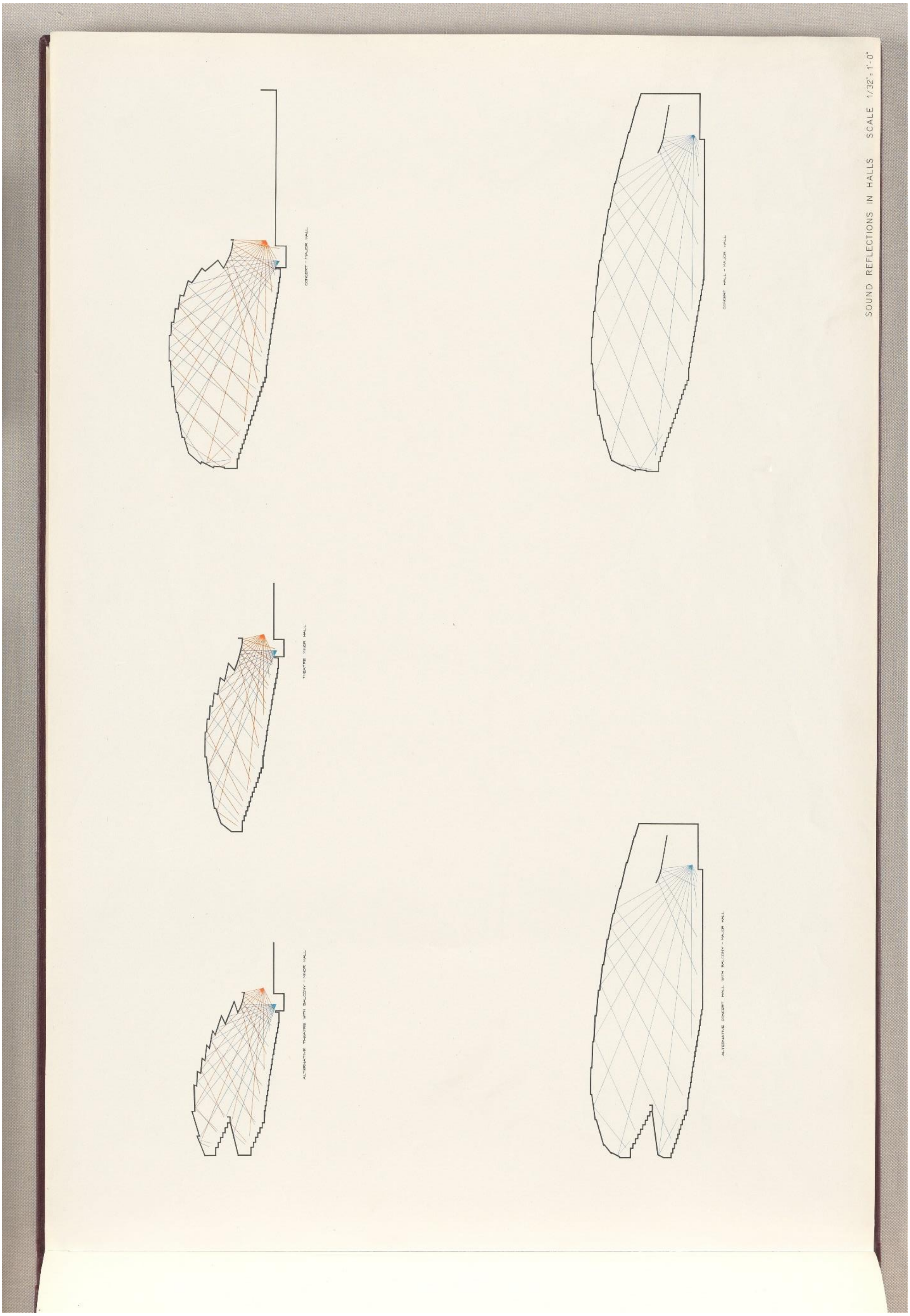
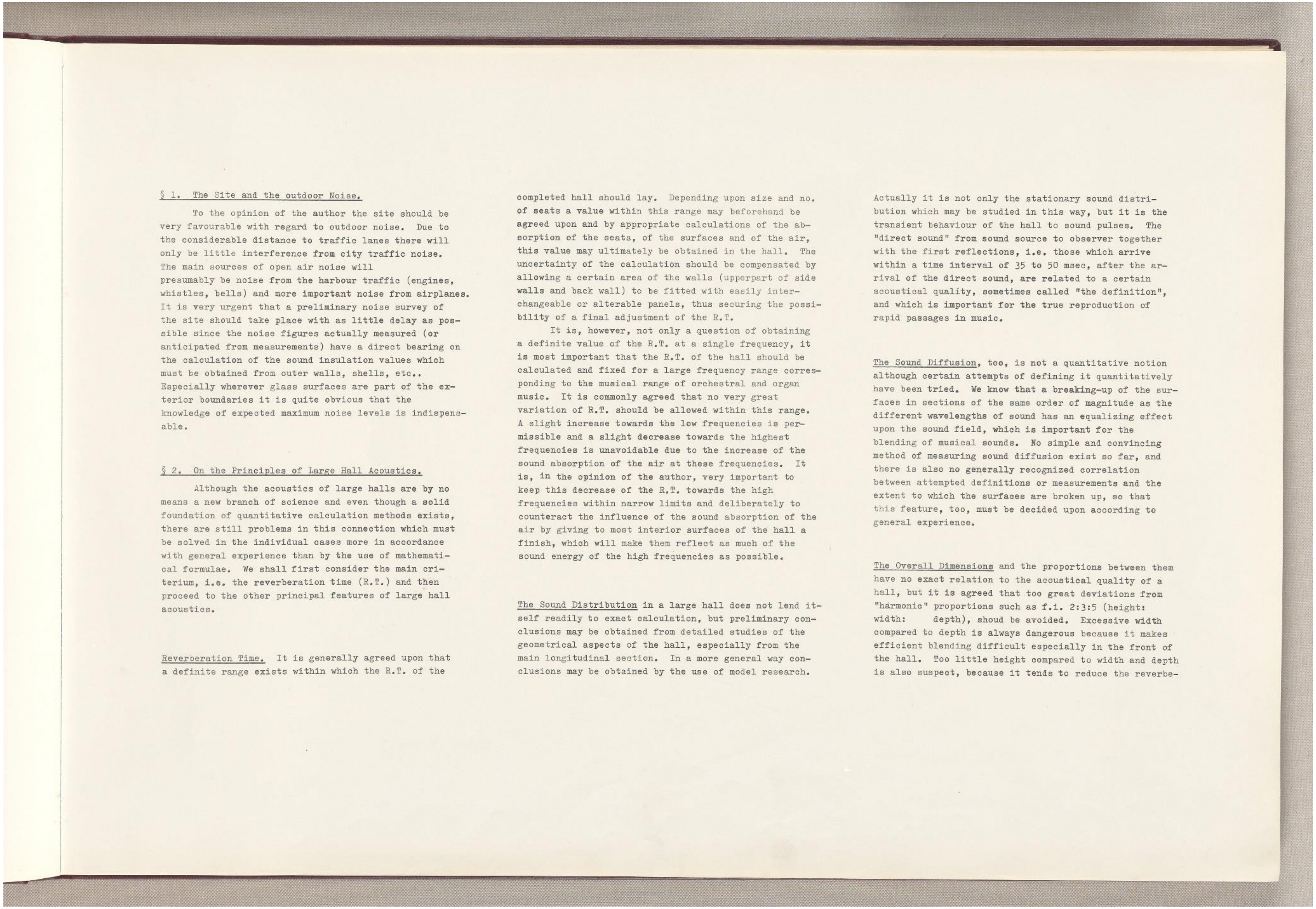


Figure 107: Sydney Opera House – Sound Reflections in Halls



§ 1. The Site and the outdoor Noise.

To the opinion of the author the site should be very favourable with regard to outdoor noise. Due to the considerable distance to traffic lanes there will only be little interference from city traffic noise. The main sources of open air noise will presumably be noise from the harbour traffic (engines, whistles, bells) and more important noise from airplanes. It is very urgent that a preliminary noise survey of the site should take place with as little delay as possible since the noise figures actually measured (or anticipated from measurements) have a direct bearing on the calculation of the sound insulation values which must be obtained from outer walls, shells, etc.. Especially wherever glass surfaces are part of the exterior boundaries it is quite obvious that the knowledge of expected maximum noise levels is indispensable.

§ 2. On the Principles of Large Hall Acoustics.

Although the acoustics of large halls are by no means a new branch of science and even though a solid foundation of quantitative calculation methods exists, there are still problems in this connection which must be solved in the individual cases more in accordance with general experience than by the use of mathematical formulae. We shall first consider the main criterium, i.e. the reverberation time (R.T.) and then proceed to the other principal features of large hall acoustics.

Reverberation Time. It is generally agreed upon that a definite range exists within which the R.T. of the completed hall should lay. Depending upon size and no. of seats a value within this range may beforehand be agreed upon and by appropriate calculations of the absorption of the seats, of the surfaces and of the air, this value may ultimately be obtained in the hall. The uncertainty of the calculation should be compensated by allowing a certain area of the walls (upperpart of side walls and back wall) to be fitted with easily interchangeable or alterable panels, thus securing the possibility of a final adjustment of the R.T.

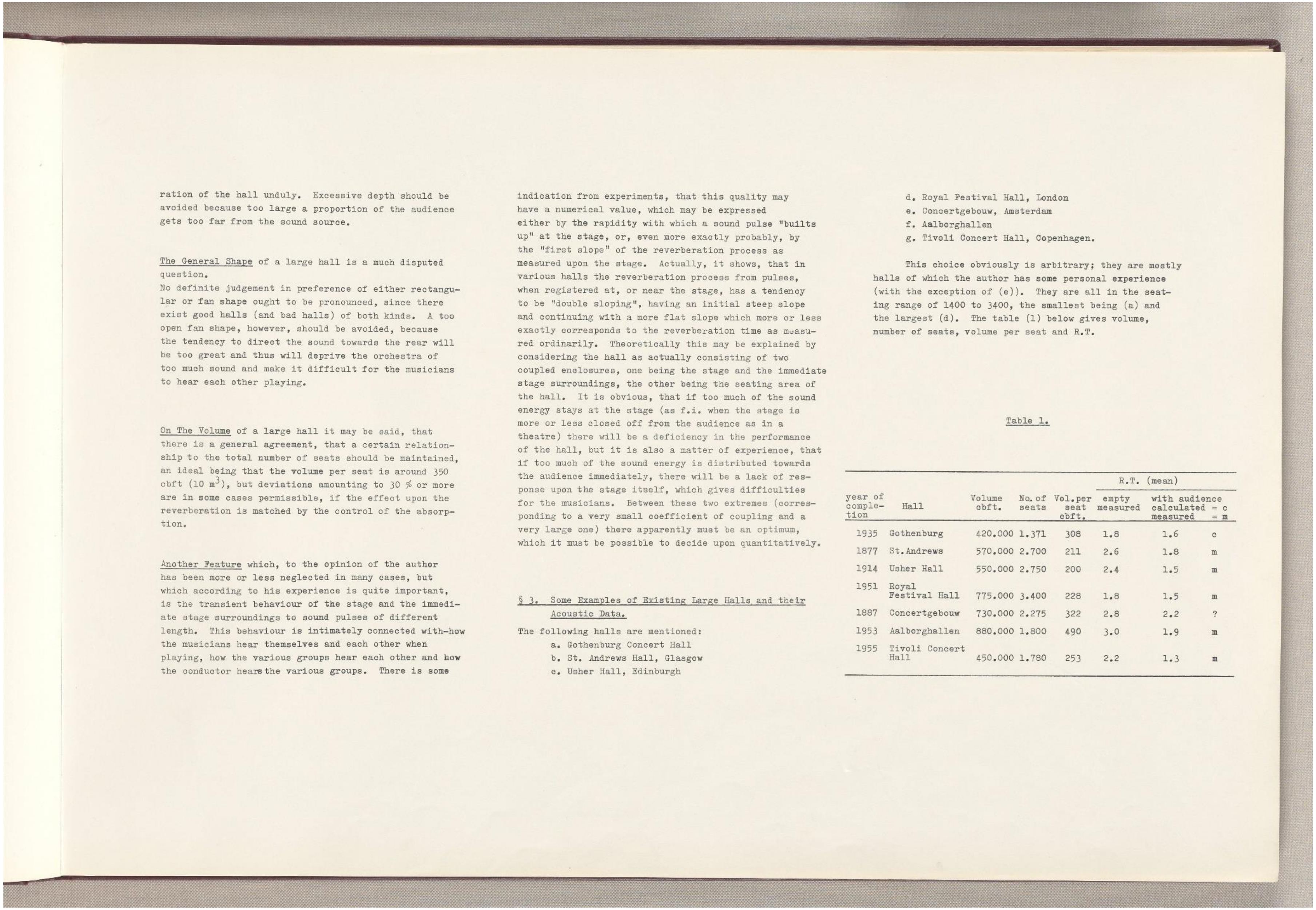
It is, however, not only a question of obtaining a definite value of the R.T. at a single frequency, it is most important that the R.T. of the hall should be calculated and fixed for a large frequency range corresponding to the musical range of orchestral and organ music. It is commonly agreed that no very great variation of R.T. should be allowed within this range. A slight increase towards the low frequencies is permissible and a slight decrease towards the highest frequencies is unavoidable due to the increase of the sound absorption of the air at these frequencies. It is, in the opinion of the author, very important to keep this decrease of the R.T. towards the high frequencies within narrow limits and deliberately to counteract the influence of the sound absorption of the air by giving to most interior surfaces of the hall a finish, which will make them reflect as much of the sound energy of the high frequencies as possible.

The Sound Distribution in a large hall does not lend itself readily to exact calculation, but preliminary conclusions may be obtained from detailed studies of the geometrical aspects of the hall, especially from the main longitudinal section. In a more general way conclusions may be obtained by the use of model research. Actually it is not only the stationary sound distribution which may be studied in this way, but it is the transient behaviour of the hall to sound pulses. The "direct sound" from sound source to observer together with the first reflections, i.e. those which arrive within a time interval of 35 to 50 msec, after the arrival of the direct sound, are related to a certain acoustical quality, sometimes called "the definition", and which is important for the true reproduction of rapid passages in music.

The Sound Diffusion, too, is not a quantitative notion although certain attempts of defining it quantitatively have been tried. We know that a breaking-up of the surfaces in sections of the same order of magnitude as the different wavelengths of sound has an equalizing effect upon the sound field, which is important for the blending of musical sounds. No simple and convincing method of measuring sound diffusion exist so far, and there is also no generally recognized correlation between attempted definitions or measurements and the extent to which the surfaces are broken up, so that this feature, too, must be decided upon according to general experience.

The Overall Dimensions and the proportions between them have no exact relation to the acoustical quality of a hall, but it is agreed that too great deviations from "harmonic" proportions such as f.i. 2:3:5 (height: width: depth), shoud be avoided. Excessive width compared to depth is always dangerous because it makes efficient blending difficult especially in the front of the hall. Too little height compared to width and depth is also suspect, because it tends to reduce the reverbe-

Figure 108: Sydney Opera House – Acoustics: (1) The Site and the Outdoor Noise, (2) On the Principles of Large Hall Acoustics



ration of the hall unduly. Excessive depth should be avoided because too large a proportion of the audience gets too far from the sound source.

The General Shape of a large hall is a much disputed question.
No definite judgement in preference of either rectangular or fan shape ought to be pronounced, since there exist good halls (and bad halls) of both kinds. A too open fan shape, however, should be avoided, because the tendency to direct the sound towards the rear will be too great and thus will deprive the orchestra of too much sound and make it difficult for the musicians to hear each other playing.

On The Volume of a large hall it may be said, that there is a general agreement, that a certain relationship to the total number of seats should be maintained, an ideal being that the volume per seat is around 350 cbft (10 m^3), but deviations amounting to 30 % or more are in some cases permissible, if the effect upon the reverberation is matched by the control of the absorption.

Another Feature which, to the opinion of the author has been more or less neglected in many cases, but which according to his experience is quite important, is the transient behaviour of the stage and the immediate stage surroundings to sound pulses of different length. This behaviour is intimately connected with-how the musicians hear themselves and each other when playing, how the various groups hear each other and how the conductor hears the various groups. There is some indication from experiments, that this quality may have a numerical value, which may be expressed either by the rapidity with which a sound pulse "builts up" at the stage, or, even more exactly probably, by the "first slope" of the reverberation process as measured upon the stage. Actually, it shows, that in various halls the reverberation process from pulses, when registered at, or near the stage, has a tendency to be "double sloping", having an initial steep slope and continuing with a more flat slope which more or less exactly corresponds to the reverberation time as measured ordinarily. Theoretically this may be explained by considering the hall as actually consisting of two coupled enclosures, one being the stage and the immediate stage surroundings, the other being the seating area of the hall. It is obvious, that if too much of the sound energy stays at the stage (as f.i. when the stage is more or less closed off from the audience as in a theatre) there will be a deficiency in the performance of the hall, but it is also a matter of experience, that if too much of the sound energy is distributed towards the audience immediately, there will be a lack of response upon the stage itself, which gives difficulties for the musicians. Between these two extremes (corresponding to a very small coefficient of coupling and a very large one) there apparently must be an optimum, which it must be possible to decide upon quantitatively.

§ 3. Some Examples of Existing Large Halls and their Acoustic Data.

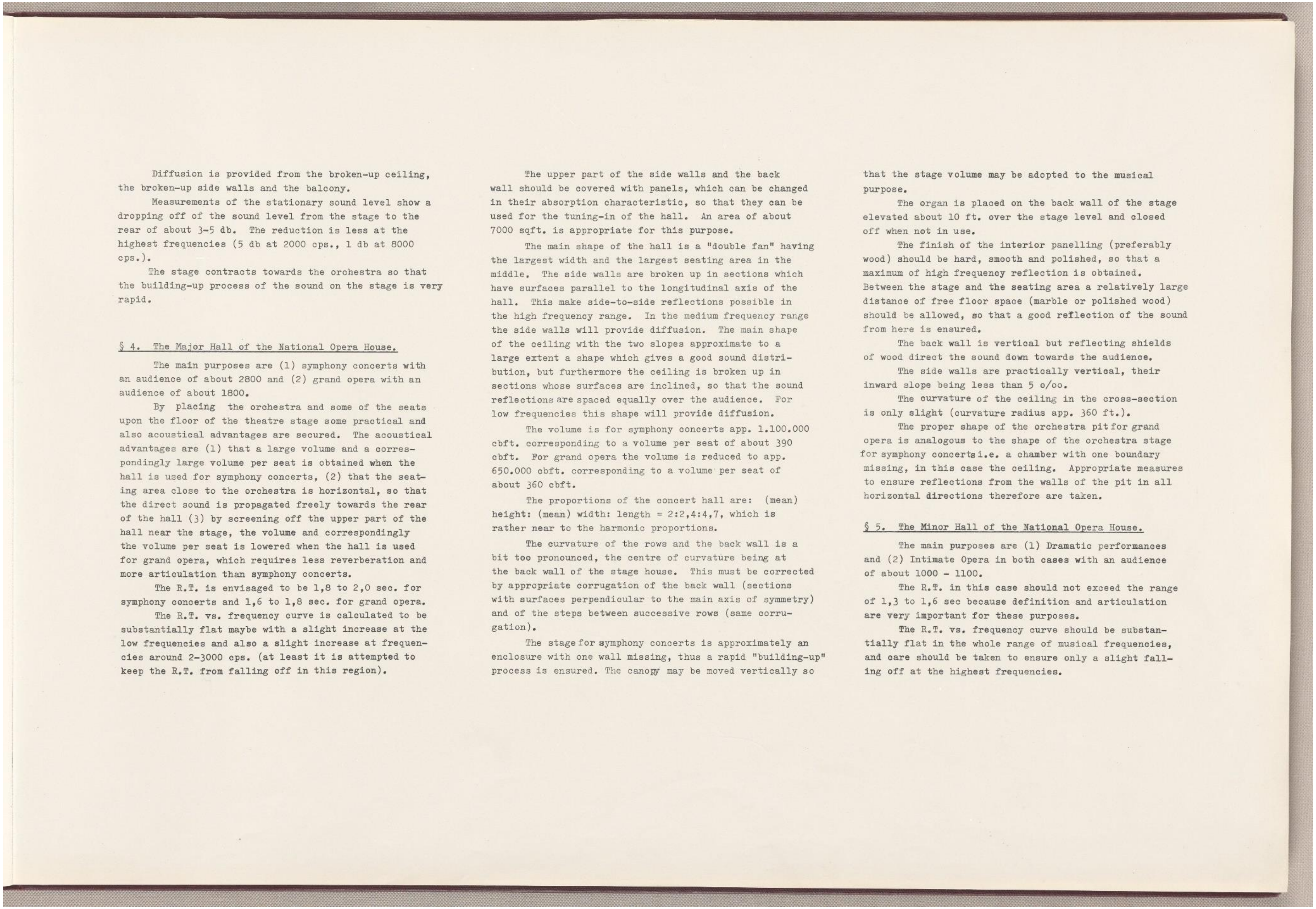
The following halls are mentioned:
- a. Gothenburg Concert Hall
- b. St. Andrews Hall, Glasgow
- c. Usher Hall, Edinburgh
- d. Royal Festival Hall, London
- e. Concertgebouw, Amsterdam
- f. Aalborghallen
- g. Tivoli Concert Hall, Copenhagen.

This choice obviously is arbitrary; they are mostly halls of which the author has some personal experience (with the exception of (e)). They are all in the seating range of 1400 to 3400, the smallest being (a) and the largest (d). The table (1) below gives volume, number of seats, volume per seat and R.T.

Table 1.

year of completion	Hall	Volume cbft.	No. of seats	Vol.per seat cbft.	R.T. (mean)		
					empty measured	with audience	calculated = c measured = m
1935	Gothenburg	420.000	1.371	308	1.8	1.6	c
1877	St.Andrews	570.000	2.700	211	2.6	1.8	m
1914	Usher Hall	550.000	2.750	200	2.4	1.5	m
1951	Royal Festival Hall	775.000	3.400	228	1.8	1.5	m
1887	Concertgebouw	730.000	2.275	322	2.8	2.2	?
1953	Aalborghallen	880.000	1.800	490	3.0	1.9	m
1955	Tivoli Concert Hall	450.000	1.780	253	2.2	1.3	m

Figure 109: Sydney Opera House – Acoustics: (2) On the Principles of Large Hall Acoustics (cont.), (3) Some Examples of Existing Large Halls and their Acoustic Data



Diffusion is provided from the broken-up ceiling, the broken-up side walls and the balcony.

Measurements of the stationary sound level show a dropping off of the sound level from the stage to the rear of about 3-5 db. The reduction is less at the highest frequencies (5 db at 2000 cps., 1 db at 8000 cps.).

The stage contracts towards the orchestra so that the building-up process of the sound on the stage is very rapid.

§ 4. The Major Hall of the National Opera House.

The main purposes are (1) symphony concerts with an audience of about 2800 and (2) grand opera with an audience of about 1800.

By placing the orchestra and some of the seats upon the floor of the theatre stage some practical and also acoustical advantages are secured. The acoustical advantages are (1) that a large volume and a correspondingly large volume per seat is obtained when the hall is used for symphony concerts, (2) that the seating area close to the orchestra is horizontal, so that the direct sound is propagated freely towards the rear of the hall (3) by screening off the upper part of the hall near the stage, the volume and correspondingly the volume per seat is lowered when the hall is used for grand opera, which requires less reverberation and more articulation than symphony concerts.

The R.T. is envisaged to be 1,8 to 2,0 sec. for symphony concerts and 1,6 to 1,8 sec. for grand opera.

The R.T. vs. frequency curve is calculated to be substantially flat maybe with a slight increase at the low frequencies and also a slight increase at frequencies around 2-3000 cps. (at least it is attempted to keep the R.T. from falling off in this region).

The upper part of the side walls and the back wall should be covered with panels, which can be changed in their absorption characteristic, so that they can be used for the tuning-in of the hall. An area of about 7000 sqft. is appropriate for this purpose.

The main shape of the hall is a "double fan" having the largest width and the largest seating area in the middle. The side walls are broken up in sections which have surfaces parallel to the longitudinal axis of the hall. This make side-to-side reflections possible in the high frequency range. In the medium frequency range the side walls will provide diffusion. The main shape of the ceiling with the two slopes approximate to a large extent a shape which gives a good sound distribution, but furthermore the ceiling is broken up in sections whose surfaces are inclined, so that the sound reflections are spaced equally over the audience. For low frequencies this shape will provide diffusion.

The volume is for symphony concerts app. 1.100.000 cbft. corresponding to a volume per seat of about 390 cbft. For grand opera the volume is reduced to app. 650.000 cbft. corresponding to a volume per seat of about 360 cbft.

The proportions of the concert hall are: (mean) height: (mean) width: length = 2:2,4:4,7, which is rather near to the harmonic proportions.

The curvature of the rows and the back wall is a bit too pronounced, the centre of curvature being at the back wall of the stage house. This must be corrected by appropriate corrugation of the back wall (sections with surfaces perpendicular to the main axis of symmetry) and of the steps between successive rows (same corrugation).

The stage for symphony concerts is approximately an enclosure with one wall missing, thus a rapid "building-up" process is ensured. The canopy may be moved vertically so that the stage volume may be adopted to the musical purpose.

The organ is placed on the back wall of the stage elevated about 10 ft. over the stage level and closed off when not in use.

The finish of the interior panelling (preferably wood) should be hard, smooth and polished, so that a maximum of high frequency reflection is obtained. Between the stage and the seating area a relatively large distance of free floor space (marble or polished wood) should be allowed, so that a good reflection of the sound from here is ensured.

The back wall is vertical but reflecting shields of wood direct the sound down towards the audience.

The side walls are practically vertical, their inward slope being less than 5 o/oo.

The curvature of the ceiling in the cross-section is only slight (curvature radius app. 360 ft.).

The proper shape of the orchestra pit for grand opera is analogous to the shape of the orchestra stage for symphony concerts i.e. a chamber with one boundary missing, in this case the ceiling. Appropriate measures to ensure reflections from the walls of the pit in all horizontal directions therefore are taken.

§ 5. The Minor Hall of the National Opera House.

The main purposes are (1) Dramatic performances and (2) Intimate Opera in both cases with an audience of about 1000 - 1100.

The R.T. in this case should not exceed the range of 1,3 to 1,6 sec because definition and articulation are very important for these purposes.

The R.T. vs. frequency curve should be substantially flat in the whole range of musical frequencies, and care should be taken to ensure only a slight falling off at the highest frequencies.

Figure 110: Sydney Opera House – Acoustics: (4) The Major Hall of the National Opera House