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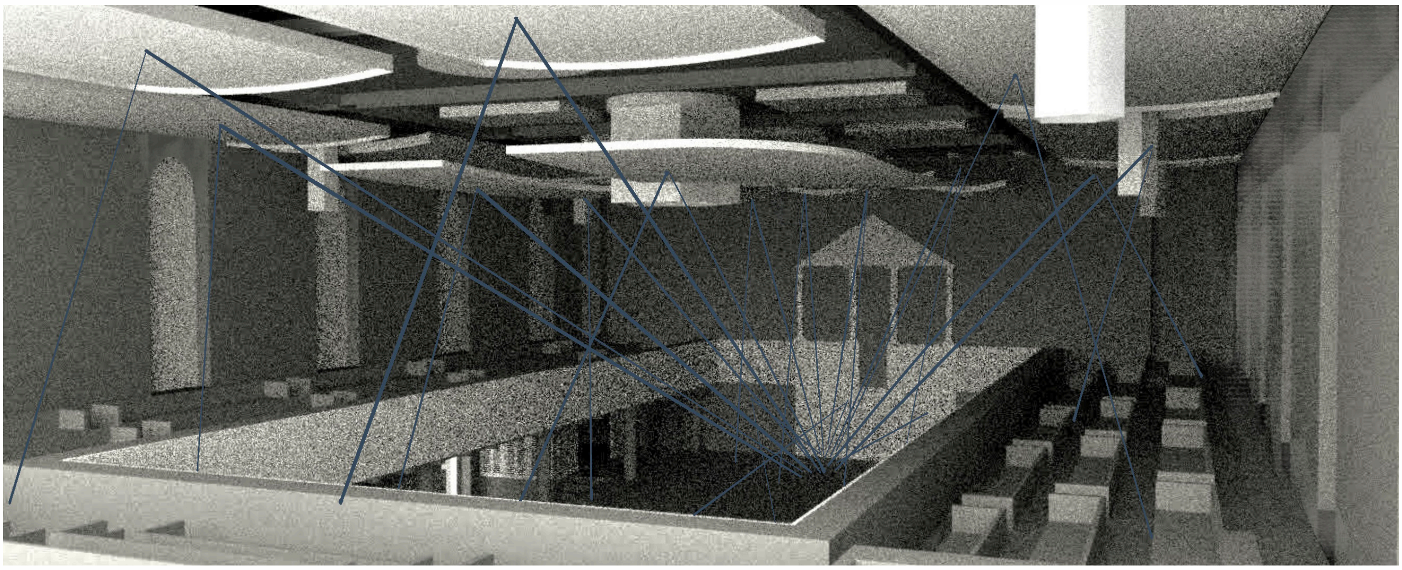
Orchestrating Architecture and Acoustics:

Exploring Sound Dynamics in Performance Venues



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STATEMENT OF OWN WORK

This study was completed as part of the Dissertation [UBLMSJ-15-3] module at the University of the West of England. The work is my own. Where the work of others is used or drawn on, it is attributed to the relevant source.

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ABSTRACT

Creating a conceptual performance venue, perhaps flexible or adaptable, must follow practical guidelines and design solutions by applying tools associated with acoustics, natural lighting, thermal satisfaction, air quality and energy efficiency. This thesis will focus on integrating the auditory dimension into an architect's design process and emphasise absorbent materials to satisfy human perception. The method to tackle this has been to examine a prominent case study and influential theory that will justify the creation of an architecture that better resonates with users and prioritises human elements.

KEY WORDS, LIST OF ABBREVIATIONS AND SYMBOLS

Note: these are terms used in the fields of architecture and engineering

Key words: Space – Perception – Transformation – Acoustics

Terms: Reverberation Time (*RT*) – Decibel (*dB*) – Frequency (*f*) – Hertz (Hz) – Absorption(α) – Background Noise Level (BNL) – Decay curve – Sabine's formula

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1. INTRODUCTION

The ability of our ears to detect sound origins enhances our qualitative navigation into space and contributes to our overall sensory experience.

- "Because there is nothing to say, not everyone is obliged to say something, but to create an atmosphere that helps us keep on living", said Sota (1991, p.124, cited in Guerra, no date, p. 189).

- "Needless to say, the same person could be both the creator of a play, its author, and one of its executors – its director or player, for instance", Krasner and Saltz (2006, p.107) emphasise.

1.1 PREFACE

An ethical stance as an architecture student is grounded in a commitment to addressing the multifaceted aspects of spatial design, including the world of music. Drawing from my background in conservatory education as a pianist, I recognise the impact that architectural acoustics possesses on the experiences of performers and audiences. I am now driven to contribute to the creation of environments that enhance both the auditory and spatial dimensions of such venues. The selection of St. George's Bristol as my case study is deliberate and driven by a nuanced understanding of how the profound silence experienced in a church acknowledges its potential to further optimise its functionality and comfort. Commemorating its 200th anniversary in the current year of 2023 leads to research on the transformative aspects it has undergone, leaving space for acoustic architects or architectural acousticians to contribute. This belief propels my commitment towards architectural acoustics, accompanied by computational design and its transformative impact on the user experience and immersion within diverse spaces.

1.2 OBJECTIVES

The objective of this dissertation is to investigate the acoustic performance of St. George's Bristol, aiming to make practical recommendations for its improvement. This involves a synthesis of theoretical knowledge from extensive literature review to an analysis of the space, leading to actionable insights in architectural acoustics.

While individual perspectives may vary, the fundamental requirements for spaces of this kind, guided by British Standards, remain consistent. The chapters converge in recognising that human perception over centuries informs our approach to spaces, inevitably created with the integration of mathematics. The cognitive map, emerging from the interaction between an environment's objective properties and a subject's perceptual abilities, acknowledges the influence of cultural preferences on reasoning. However, this does not diminish the necessity of adhering to parameters for auditory well-being, in harmony with other human senses regardless of one background epistemology (Norenzayan *et al.*, 2002).

The transformation and reconstruction of the case study, driven by user satisfaction and compliance with regulations, underscore its evolution into a more flexible and dynamic event space. Notably, spatial organisation tends to linger in memory more than individual elements such as shape or decoration (Noë, 2021). An emphasis on the importance of meticulous planning from the outset is stated. Nonetheless, the narrative also acknowledges the capacity for adaptive alterations in response to changing needs, affirming the ongoing relevance of well-considered spatial design.

1.3 METHODOLOGY

The focus of this study revolves around the critical elements of reverberation and the decorative aspect of absorption that complements it. The research employs practical data collection techniques, including applying fundamental mathematical principles, primarily Sabine's formula, while adhering to optimal sustainability and acoustic targets following the British Standards Institute (BSI) and the International Organization for Standardization (ISO). 'Acoustics - Measurement of room acoustic parameters, Part 1: Performance Spaces (ISO 3382-1:2009)' informs the body of this study.

Through an extensive review of existing studies and theories, this research aims to demonstrate how these theoretical foundations manifest in the infrastructure and environment of a real-world venue, St. George's Bristol. It will investigate the challenges faced to attain a high level of sound and structural isolation between the new, potentially multi-purpose areas, and the original church building housing the primary concert hall. A gunshot test, as an impulse source, and an evaluation of the background noise level (BNL) with BSI indications have mainly been employed. While obviating its efficacy after testing the concert hall, further design proposals and in-person interactions will be illustrated.

Multiple visits to the concert hall are intended to justify a compelling and evidence-based argument, combining empirical data with constructive critique. This approach aims to extend our understanding of relevant issues highlighted in the literature review, underscoring the critical role of architectural acoustics. Emphasising the importance of comfort in performance venues, this study seeks to challenge our perceptions in both auditory and spatial dimensions, potentially shaped by architectural design.

1.4 STRUCTURE

This research involves a gradual exploration of architectural acoustics. Commencing with a comprehensive overview encompassing the historical evolution, origins, and potential influences from psychology shaping individual perception within this environment, we traverse through antiquated concepts that have catalysed advancements in engineering and mathematics. This examination reveals the persistent utilisation of these terms in British Standards dictating the acoustic suitability of spaces intended for human habitation and creation.

The literature review continues with a specific case study, St. George's Bristol, to analyse its historical evolution and contemporary renovations (Figure 1). Moving beyond archival exploration, we immerse ourselves in the concert hall that the building hosts, executing a detailed acoustic evaluation guided by real-world parameters. These tests encompass assessing background noise levels and introducing an impulsive sound source to gauge the site's optimal acoustic conditions, with particular emphasis on reverberation. The subsequent discussion details the nature of our conducted tests, linking the gathered data to users' insights.

Figure 1: Original façade with conteporary poster of venue

2.1 A blend of history, culture, philosophy and modern transformation in architectural acoustics

Architectural design and its evolution over time explore building typologies while offering a space for the auditory dimensions to develop simultaneously. Regardless of the architectural style, they are interwoven with the building's structure, language and functionality while adhering to suggested Standards. We investigate the fusion of acoustic theory and its practical implementation, underscoring their combined influence in creating spaces that resonate with architectural identity and serve the comfort and requirements of the community.

Embracing space transformation in performance venues has involved a multisensory experience to "give coherence and precision to the notion of stage presence" (Krasner and Saltz, 2006, p.122), merging physical sensations and rhythm. These last shape our perception of temporality in response to the environment. As we conceptualise a space, we move from a phase of exploration to a final exhibition plan, a more tangible representation. This tangible representation evokes more real experiences in which we must be aware of elements like the number of steps and their dimensions. These become essential considerations and allow users to navigate space smoothly (see Figure 2).

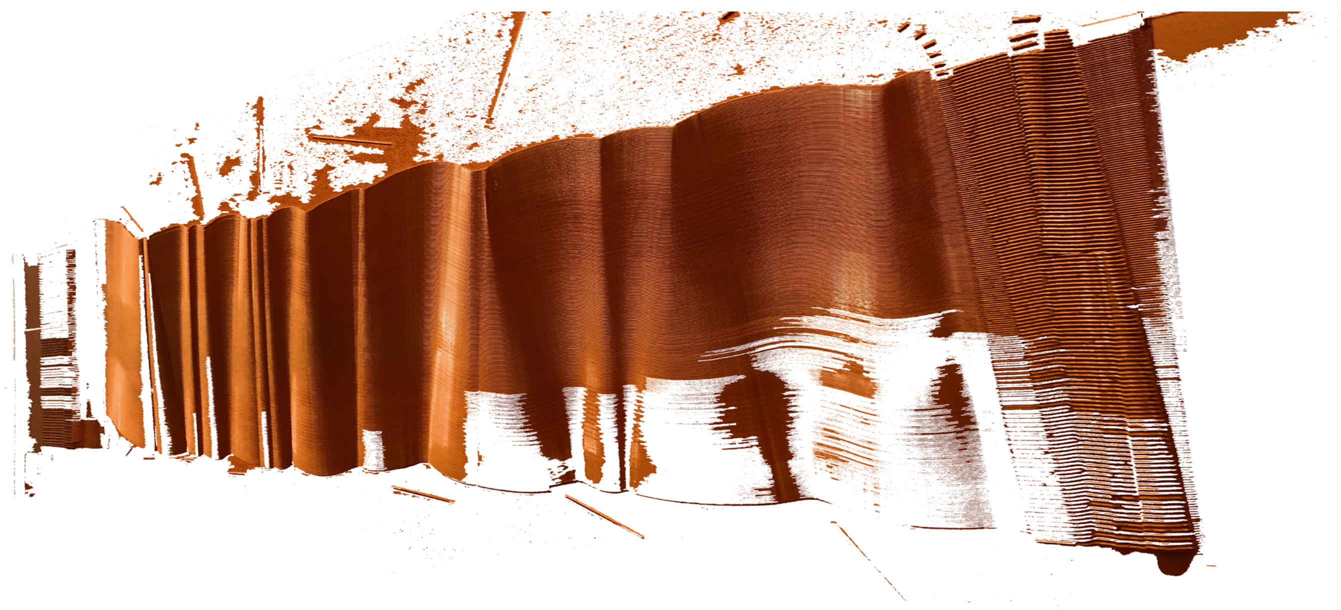

Figure 2: Motion, perspective, waves and proximity

Departing from the Greek philosophical traditions of seeking to understand the world, we enter a society of the spectacle, symbolised by open theatres later refined by the Romans (VI B.C. to I A.D.). Advanced engineering was emerging and led to optimising human comfort by, for example, crafting the vomitorium, or *vomitoria*, for exit passages offering quicker circulation to spectators and adding balconies to enhance the viewing experience of the scene or *scaena*. The nature of these spaces integrates specific rules first explored by the Greek sculptor Phidias. He stated that the beauty of the Parthenon was due to proportions, similarities between parts and mathematical relations. The German astronomer and mathematician Johannes Kepler, then describes this spatial relation, or Golden Ratio, based on the number of approximately 1.618 as the number Phi to honour Phidias. La Divina Proportione (1509), by the Italian mathematician Luca Pioli, then shaped that human perception was based on a divine proportion. The Roman architect and engineer Vitruvius further studied geometry during the 1st century (Martínez Lara, 2023). He placed these discoveries in the layout of the open-air theatres of the time and was mostly concerned about acoustics rather than vision (Beranek, 1996). The merging of these through testing and evaluation led the audience to immerse themselves in the show rather than worrying about the external world, despite the culture and the geographical region.

In contemporary architectural discourse, ancient Greco-Roman principles direct our focus towards cognitive perception. Alva Noë introduces the empiricist theory, which remains closely tied to our experience of the world through individual senses. This theory justifies our knowledge of physical movements, easily tested by closing one of our eyes, or ears, while focalising the other. For instance, closing one's preferred eye can lead to a concentrated, even transformed perception akin to the concept of a focal or vanishing point in technical drawing terminology (Noë, 2004). While this may induce a sense of asynchronism, it is an individual transient experience offered to, as Krasner and Saltz (2006, p. 122) state, "those for whom the lived phenomenon of presence still makes sense and is borne out in practical experience" given the current circumstances. Ernst Mach's Self-Portrait from 1886 (Figure 3) depicts an example. Architecture and psychology met in the 1970s and contributed to our comprehension of future spatial and technological arrangements. This juncture made the term 'aesthetics' emerge, enhancing the capacity to reimagine existing spaces. For example, the German composer Richard Wagner's imagination of theatres and the path towards a Baroque style came with new forms and textures (Obracaj, 2020, pp.55-60; Izenour, 1996). Achieving this involves employing stimulation methods that assess our reactions to new spatial representations, which our minds tend to idealise while simultaneously distorting due to factors such as limited sensory input, context, and scale (Figure 4). These perceptive-cognitive activities also encompass our memory. Involuntarily, we recollect the journey to a place, the promenade through space, and occasionally, we can mentally retrace our steps. This retrospective act engages with our understanding of the environment, considering its aesthetics and function in spatial organization. Our holistic experience is a result of the intricate interplay between design and psychology within individual experience, intertwined with cultural and personality factors (Rasmussen, 1962).

Figure 3: Self-Portrait by Ernst Mach (1886)

Colin Ellard, an English neuroscientist, states that certain 'echoes' exist within our minds that seek to comprehend the natural world around us. Climatic and geographic factors determine our decisions that inform our adaptability to a given space (Larrea Sánchez, 2018). Ellard (2016) emphasises that a geometrical understanding is consistently employed in 'psychogeography', regardless of the scale of observation. Consequently, we infer that these inherent geometric patterns provide a sense of pleasure to our minds and contribute to an aesthetic experience.

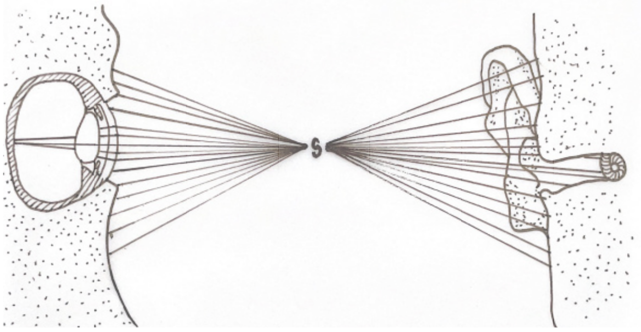

Figure 4: Vision, hearing and seating (Izenour, 1996)

2.2 Case Study: The history of St. George's Bristol and its relation to the existing body of knowledge

Figure 5: Old and new façades framing path

The journey towards and inside St. George's Bristol encapsulates the essence of architectural adaptability, where historical preservation, acoustic pollution and sustainability converge. This evolution resonates with the golden ratio, emphasising the harmony between aesthetics and acoustics. "It is possible to 'hear' the music of visual proportion" (Calovski, 2022, p. 41; Le Corbusier, 1955, p. 148)".

St. George's Bristol stands as a remarkable architectural gem since 1820 in the heart of Bristol, United Kingdom, offering a unique blend of history, acoustic excellence, and modern functionality (see Figure 6). This independent music venue hosts a 200-year-old Georgian church that has undergone a transformation rooted in the world of architectural acoustics. Its narrative indicates how a sacred space evolves with time to meet modern demands while adhering to sustainable and regulatory standards within the new 580-seat concert hall. Its strategic location, surrounded by history and greenery, is away from the main road, contributing to its charm. Despite its residential surroundings and limited accessibility by car due to the city's Clean Air Zone policies, St. George's Bristol remains a welcoming haven for music enthusiasts and architectural ‘aficionados’ alike. In this urban context, acoustic pollution is a pressing concern, affecting residents’ quality of life and the urban environment. Architectural construction and vehicular noise pose challenges, making it imperative to consider isolating materials and urban planning strategies in future developments.

In 2012, Patel Taylor Architects visualise the historical significance of the Grade II* Listed concert hall while aiming to extend its capabilities (Patel Taylor Architects, 2018). The extension project sought to enhance the visitor experience to, as the German composer and pianist Beethoven said, offer the ‘architecture as a music of stones and the music as an architecture of sounds’ (Escoda Aroca, 2017). These spaces include a welcoming café-bar, multipurpose learning and rehearsal areas, and back-of-house facilities for management and performers. A harmonious integration is brought on the strong topographic lines of the churchyard, into which the venue is nestled. This slope allows the old and new elements of the building to coexist organically, creating a fluid transition between indoor and outdoor spaces.

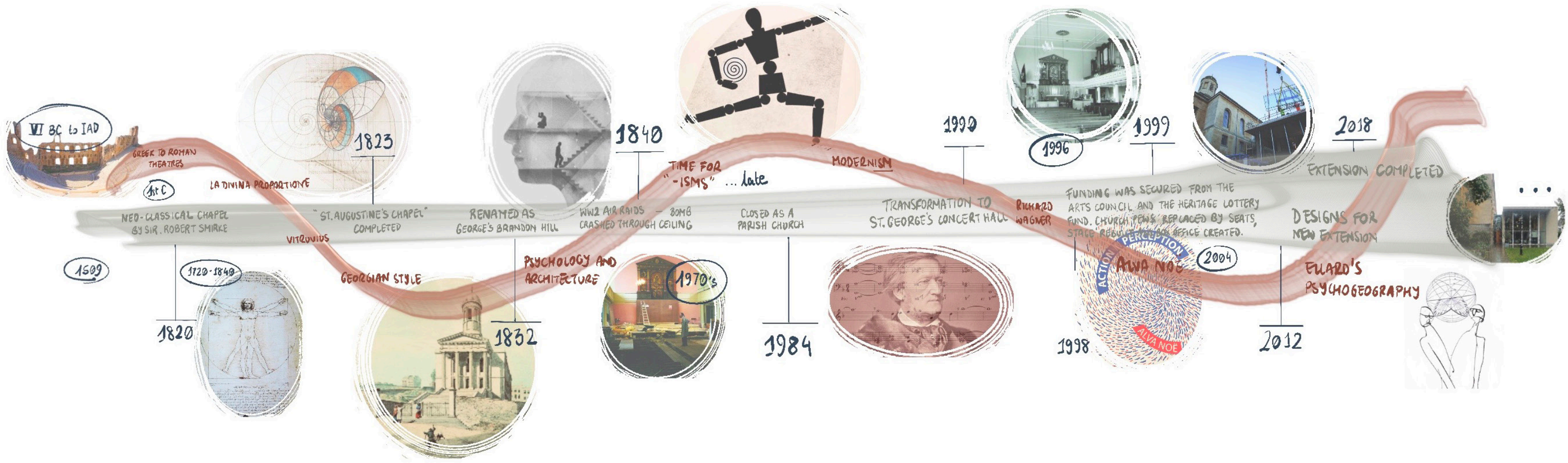

Figure 6: Historical events into St. Georges’ transformation

The design approach preserves the historic fabric while introducing contemporary elements. The glazed link between the buildings creates a transition space bathed in natural light. A contrast between the mediation of spaces rises with the interplay of lighting towards the lower levels. The crypt is preserved, while a new modern integration is developed. The upper floors of the venue are dedicated to rehearsal, performance, and study spaces, where the oculus draws in natural light. The successful use of natural and cross ventilation, kitchen extraction, and mechanical ventilation with heat recovery in the café-bar area, underscores the meticulous planning that went into optimising interior temperature. Solar and thermal qualities, ventilation strategies, and the use of advanced materials contribute to reducing operational carbon. Replacing boilers with air-source heat pumps exemplifies its dedication to environmental responsibility towards an optimal building life cycle. The integration of active environmental systems (Figure 7) exemplifies the venue’s commitment to sustainability recognising ISO 14001 as the standard for environmental management systems (EMS) (Ferguson Mann Architects, 2024).

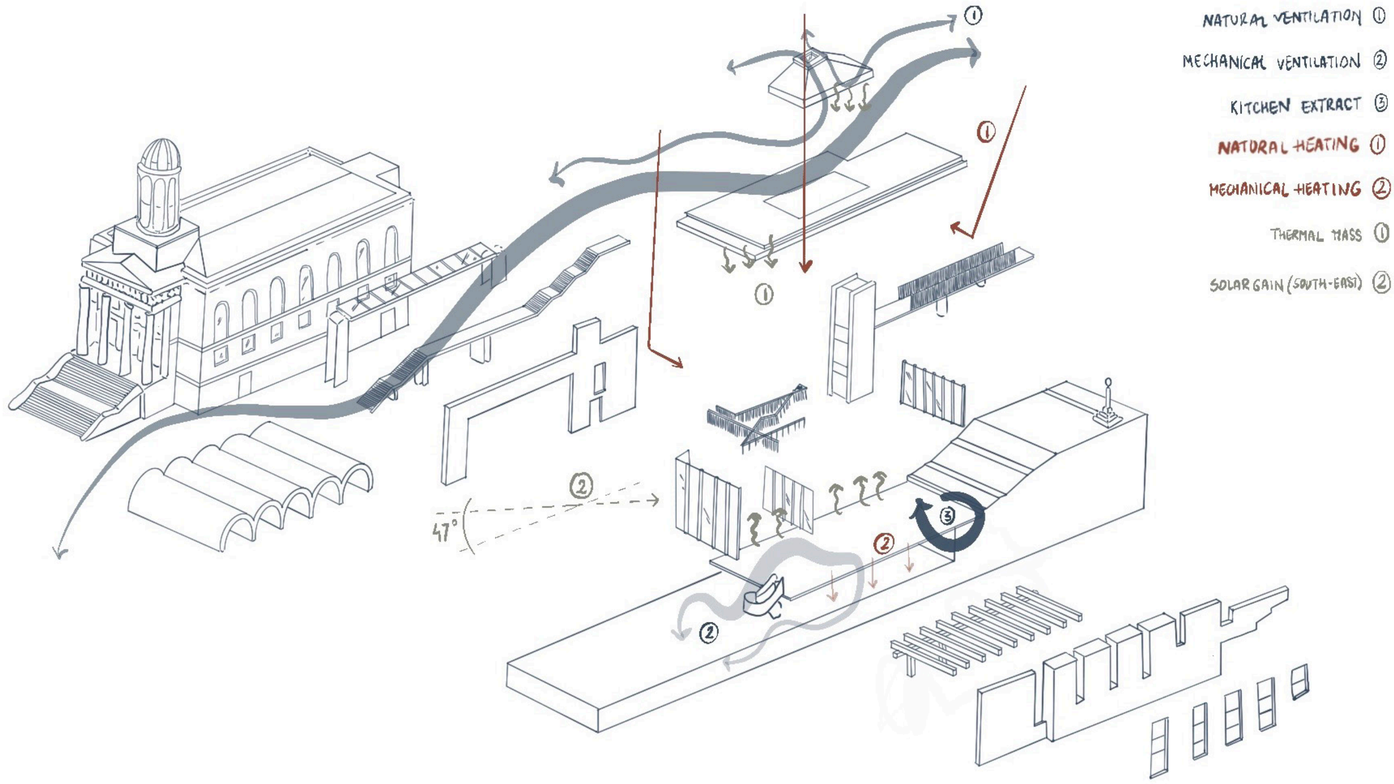

Figure 7: St. Georges’ Bristol environmental analysis

The fabric evokes sensory experiences from the promenade that leads to the building. The bath stone used in the southern façade blends with the original façade of the church despite it being structurally independent (see Figure 8). The venue employs a hybrid strategy for the flow of the building, highlighting the importance of sound and structural separation to prevent disruptions during events or rehearsals. Façade engineering is characterised by elements such as pre-cast concrete overhanging roofs, glazing, steel mullions, transoms, and metal cladding. These features not only enhance the building's aesthetic appeal but also integrate passive temperature regulation, thereby improving its thermal mass. High-performing secondary glazing, acoustic doors, and aluminium framed windows contribute to sound insulation and maintenance towards the interior. Thoughtful terracing solutions dealing with the sloped site showcase the fusion of architectural and acoustic considerations.

Figure 8: Contributions to sound isolation

St. George's Bristol, with its historical significance and architectural splendour, inspires future renovation projects seeking to seamlessly blend timeless aesthetics with acoustic innovations. A theoretical framework on principle rules is necessary for further specific understanding of the concert hall.

3. THEORETICAL FRAMEWORK: Architectural acoustics terminology

Architectural acoustics is a multifaceted department that merges architecture and engineering while playing a critical role in designing spaces that affect auditory and neurological needs. A specific terminology around the world of physics comes with the field of sound and explains phenomena that question the subjective human experience or perception (RIBA, 2020). Focusing on Reverberation time (RT) and background noise (BNL), we focus on regulatory guidance shaped to indicate recommendations to the theme. These include building regulation on Approved Document Part M (Access to and use of buildings), Part E (Resistance to the passage of sound), ISO 3382-1:2009 (Measurement of room acoustic parameters), ISO 23591: 2021 (Acoustic quality criteria for music rehearsal rooms and spaces) and PAS 6463: 2022 (Design for the mind – Neurodiversity and the built environment – Guide).

The Canadian composer R. Murray Schafer (1994) delves into the theme of 'soundscapes' and explores, "Is the soundscape of the world an indeterminate composition over which we have no control, or are we its composers and performers, responsible for giving it form and beauty"? Psychoacoustics and the human ear's mechanism come along, which can understand acoustical principles, eventually gaining the ability to shape our environment. Key concepts to the theme are listed in PAS 6463 (2022), indicating a balance between stimulation and background noise to achieve an optimal auditory perception. This involves zoning in environmental acoustics and comprehending the behaviour of sound in various settings. These noises originate from external to internal factors, such as traffic, mechanical systems, or the specific use of a room. Therefore, the objective is to optimise acoustics by isolating spaces according to their designated purposes.

Promoting this well-being is crucial and must be done by understanding the term 'reverberation'. Reverberation time (RT), introduced by the American physicist W.C. Sabine in 1898, is a key concept indicating how long it takes for sound pressure level (SPL) to decay by 60dB after the source stops (Szlapa *et al.*, 2016), expressed as:

$$RT = 0.161 \frac{V}{A}$$

When entering performance venues, we must understand that this phenomenon is inversely proportional to the absorption capacity of the room. The reverberation time informs the absorption and vice versa. By obtaining the direction and reflection of sound, we can introduce materials that tackle either excessive reverberation or insufficient sound isolation neurologically experienced in a space. We draw insights from aesthetic values with acoustic innovations, showcasing our ability to create optimal thresholds that, as Rasmussen (1959, p.224) explores, 'hear architecture' (Díaz Gallardo, 2019, p. 36). The clarity of sound, or 'Deutlichkeit' (Beranek, 1996) as Danish astronomer T.N. Thiele defined it, is another critical aspect, especially in auditoriums. This ratio compares the initial milliseconds of the sound source and the total energy received by the listener. Understanding and applying these concepts ensures that the auditory experience in performance spaces, whether for music or speech, is optimal. The frequency is defined as the number of oscillations per second measured in Hertz. This exerts a significant influence on sound perception and the psychoacoustics of the human ear. This content of the sound in an auditorium, as obtained from a sound pressure study, is relevant as it may be absorbed or reflected differently, affecting energy distribution and clarity (Rovira Bonilla, 2019).

Decor elements contribute to reflection, diffusion, absorption, and dampening for the desired acoustic environment. This aesthetical interplay should shape the materials into forms and patterns that enhance the perception of performers or audience members. It becomes evident that certain materials complement one another, while others are incompatible depending on their allocation in the room. It is a well-established fact that "the human auditory range of the ear falls between 20Hz to 20kHz" (Purves *et al.*, 2001) and a robust site analysis of possibilities must therefore be considered. An excess of reflective surfaces can result in undesirable echoes and the formation of eigenmodes, a key to enriching reverberation time and sound pressure level disparities (Lokki *et al.*, 2015). While this remains true, the increase in early lateral reflections leads to heightened dynamic levels, a key element in high-quality concert hall acoustics (Barron, 2019). Because of this, consulting acoustic standards and guidelines is crucial in this process for optimal experience.

With development, computational design plays a big role in enhancing acoustic outcomes. Experimenting with varied materials and designs virtually, thus predicting them, enables designers to simulate and optimise acoustic environments more precisely.

4. TEST REPORT

St. George's Bristol concert hall was analysed in an unoccupied state by a team of four following BS EN ISO 3382-1:2009: Acoustics – Measurement of room acoustic parameters. Part 1: Performance spaces. RT and BNL were primarily measured:

TEST REPORT	
"The test report shall include the following information" (ISO 3382-1, 2009, p.11):	
a) A statement that the measurements were made in conformity with this part of ISO 3382;	This study was completed as part of the Dissertation module for BSc(Hons) Architecture course at the University of the West of England. "Where the work of others is used or drawn on, it is attributed to the relevant source".
b) Name and place of the room tested;	St. George's Bristol Concert Hall
c) Sketch plan of the room, with an indication of the scale;	Figure 9
d) Volume of the room;	24.64 · 17.14 · 8.59
e) For rooms for speech and music, the number and type of seats;	580 seats: Upholstered wooden seats
f) A description of the shape and material of the walls and the ceiling;	Rectangular, shoebox shape with balconies. Hard wood with textured surfaces and plasterboard
g) State or states of occupancy during measurements and the number of occupants;	4 occupiers testing acoustics
h) Condition of any variable equipment such as curtains, public-address system, electronic reverberation enhancement systems, etc.;	Doors closed, existing curtains closed (covered surfaces)
i) For theatres, whether the safety curtain or decorative curtains were up or down;	Curtains closed
j) Description, where appropriate, of the stage furnishing, including any concert enclosure, etc.;	Wooden floor on stage with existing mural (closed with a curtain on the main floor and exposed on the balcony level). The sides of the stage also have curtains and contain another piano, music equipment and furniture such as extra chairs.
k) Temperature and relative humidity in the room during the measurement;	Temperature: ±20.6°C; Relative humidity: ±56.1% R.H.
l) Description of measuring apparatus, source and microphones, and whether tape recorders were employed;	Omnidirectional sound level meter (reverberation time analyzer): Brüel & Kjær, type 2250-F/BZ-7227, 1.2m high on 6 different positions; Reference sound source: Brüel & Kjær, type 4204, on stage to obtain background noise level (BNL)
m) Description of the sound signal used;	Impulse source: Pistol/firearm discharge (muzzle blast/gunfire) propagating away from shooter in all directions for gunshot test. 2 positions on stage, 6 shots. Captured by RT analyzer (6 positions, 3 for each of the 2 positions of the impulseive source)
n) Coverage chosen, including details of the source and microphone positions, preferably shown on a plan, together with the heights of the	Figures 10 and Figure 11

Table 1: Test report

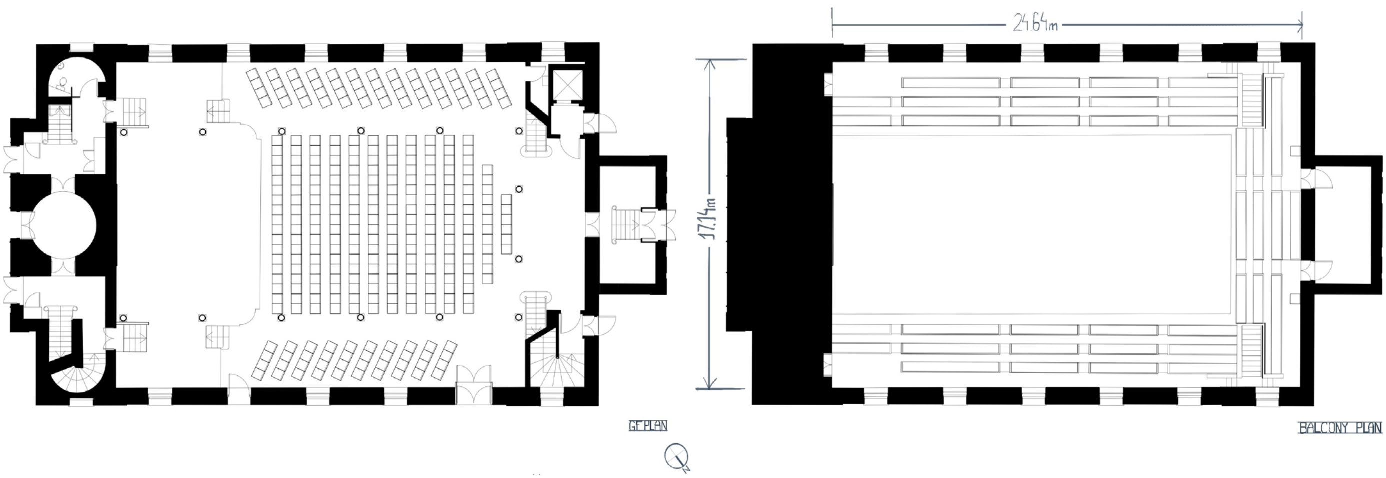

Figure 9: St. George's Bristol venue plans

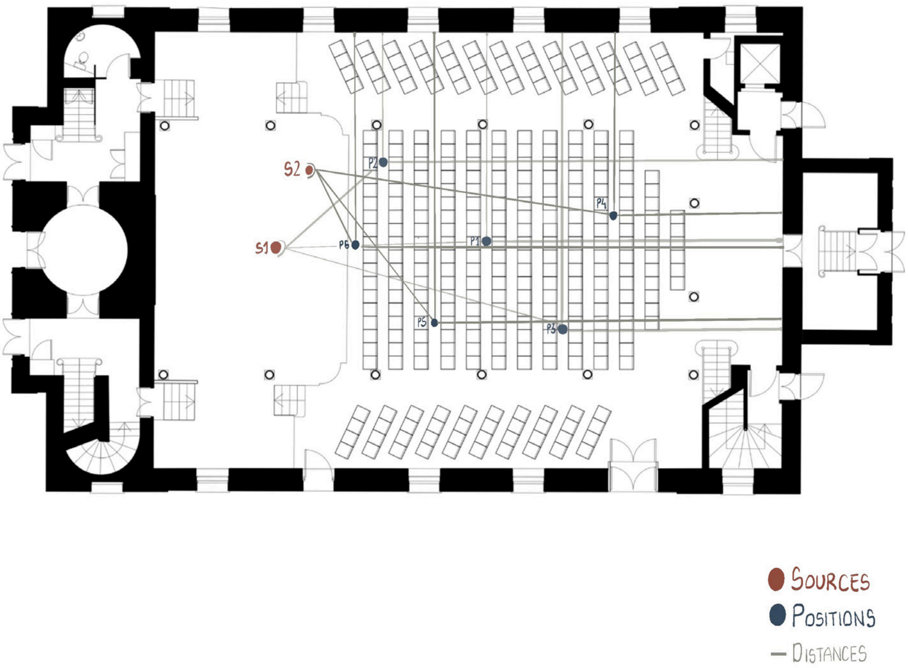

Figure 10: Source and microphone positions on plan

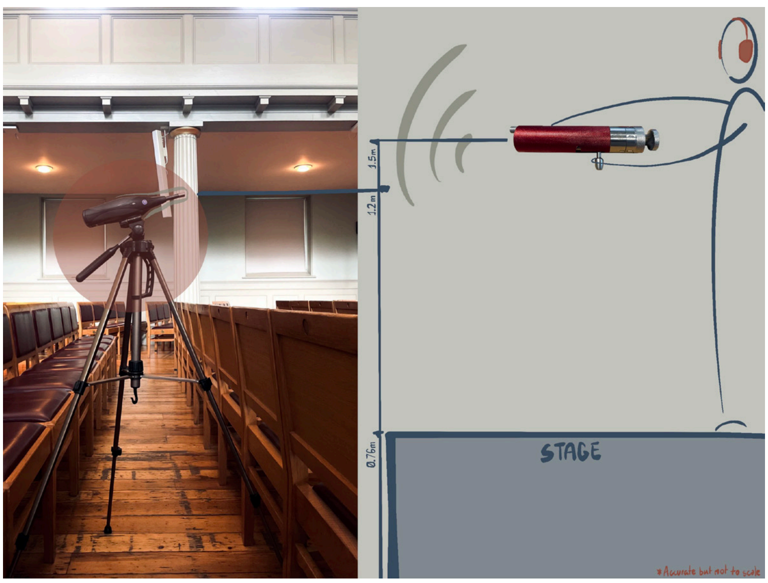

Figure 11: Source (handgun) and microphone heights

5. CASE STUDY – A DISCUSSION OF ST GEORGE'S CONCERT HALL

5.1 Test report analysis and observations

The testing of St. George's Bristol concert hall (Table 1) was carried out in an unoccupied state (ISO 354:2003, 3.6.1) by a team of four, equipped with various tools such as a measuring tape and laser range, a whirling hygrometer for temperature and humidity and a stopwatch (Figure 12). The primary instrument for acoustic measurement included an omnidirectional microphone attached to a Brüel & Kjær 2250 4G sound level meter, which captured data from both the handgun as an impulsive source.

The testing process considered the hall's dimensions, orientation, and unique architectural features such as the stage, wall and ceiling textures, backstage areas, balconies, and the existing furniture, including a grand piano. Particular attention was paid to the audience area, considering the number of seats, covering materials, and accessibility. The team also recorded the entrances, exits, and fire exits, as well as the location of audio-visual equipment and the large windows with blinds. The team noted there were original murals on the stage end of the church, currently concealed by curtains on the main floor. With the acoustic test results, the team decided whether to treat or change these elements, informed by absorptive coefficients before aesthetics.

The testing began by measuring the temperature and humidity, obtaining ±20.6 °C (343 m/sec at 20°C) and ±56.1% R.H., which states how fluctuations in humidity could impact the sound and condition of wooden instruments such as grand pianos. A background noise level test using a sound frequency analyser, measured in octave noise bands while determining the A-weighted sound

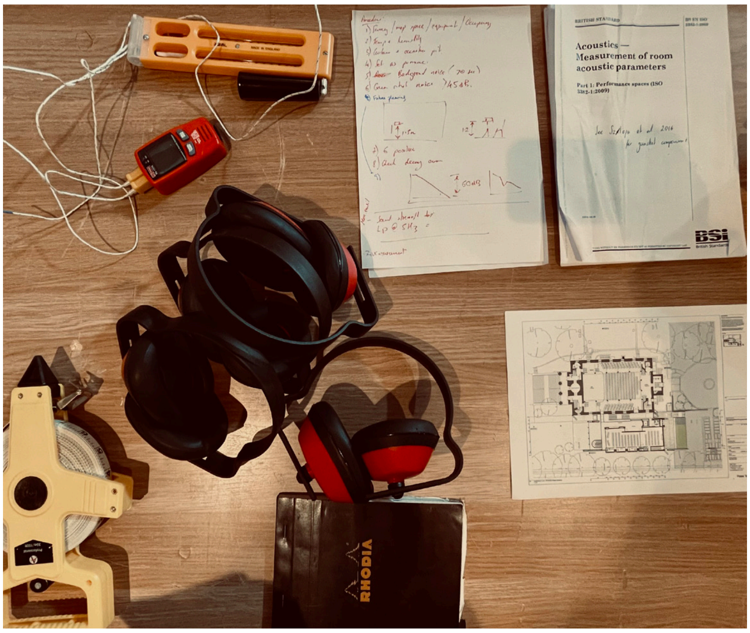

Figure 12: Materials for survey

pressure level (BSI, 2021). The sound source underwent a 30-second calibration, adjusted to align with human ear sensitivity, and was set to emit a sound power level (Lw) of 91dB at a frequency of 50Hz. The sound level meter indicated an acceptable background noise level of LAeq 24.45 (Figure 13), within the ideal range of 25-30dB (see Table 2) for this specific space (Archtoolbox, 2024).

ROOM / SPACE	DBA	NR	NC/NCB	RC/RCM2
Theaters, Concert Halls, Recording Studios	25-30	20	10-20	20
Bedrooms, Libraries, Religious Prayer Rooms	25-30	25	20-25	25
Living Rooms, Classrooms, Lecture Halls, Conference Rooms	30-35	30	30-40	30
Offices, Courtrooms, Private Work Rooms	40-45	35	30-40	35
Corridors, Open Offices, Bathrooms, Toilet Rooms, Reception, Lobbies, Shopping	45-55	40	40-40	40
Kitchens, Shopping, Common Spaces, Dining Halls, Computer Rooms, Workshops	45-55	45	40-50	45

Table 2: Acceptable sound level for concert halls

This led to obtaining a noise rating. Using the provided chart (Figure 14), it is observed that the noise rating (NR) curve is primarily influenced by frequencies ranging from 500Hz to 8000Hz. Notably, there is a pronounced high-frequency noise between 1 and 2 kHz. The absence of significant peaks suggests effective isolation between the original structure and the new extension of St. George's Bristol. This level of sound isolation not only adheres to but also surpasses the relevant acoustical standards, indicating a structurally satisfactory sound design.

Figure 13: Background noise frequency analyzer

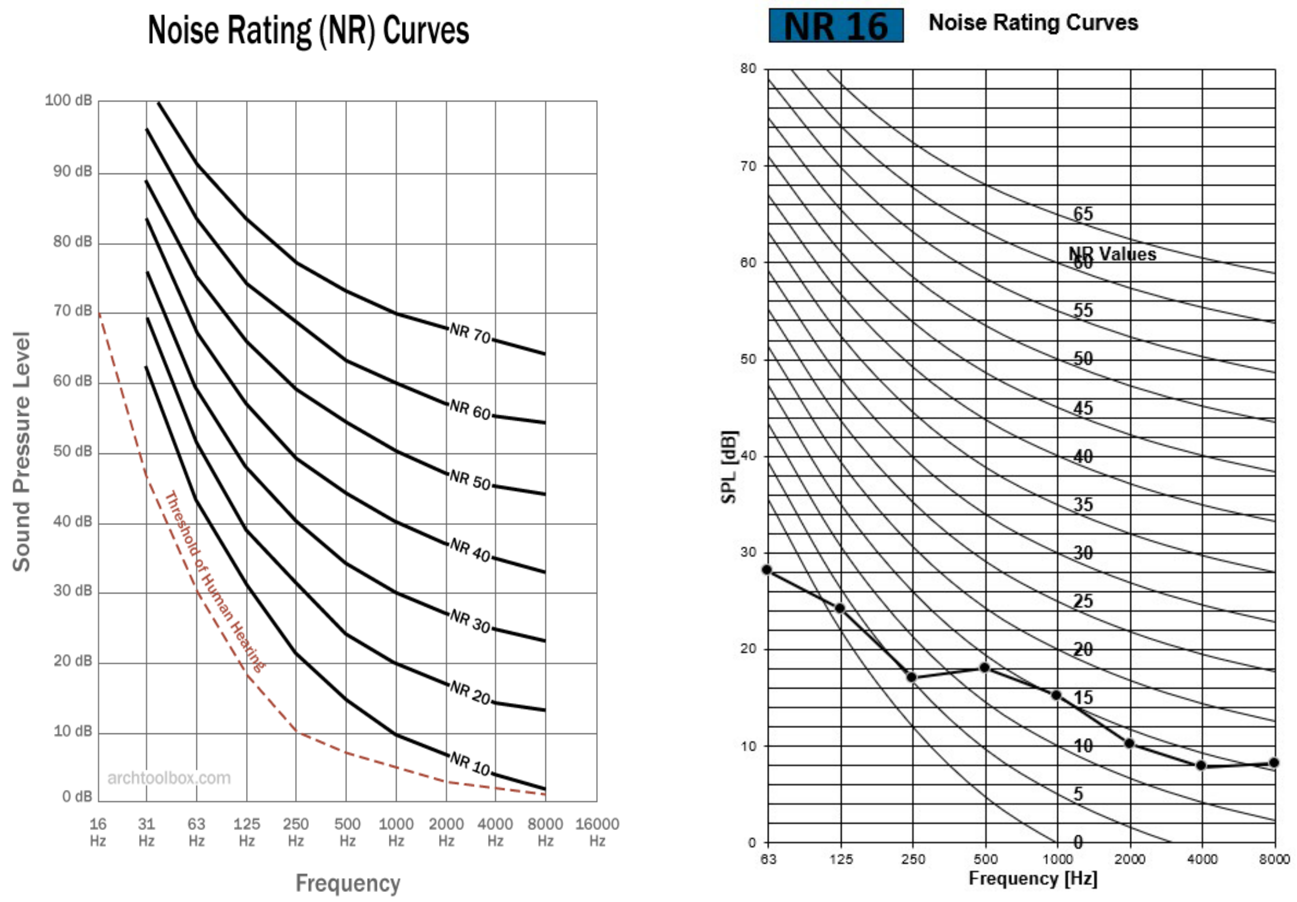

Figure 14: Noise Rating Curve example (left) and St. George's results (right)

Next, a gunshot test was conducted to assess the hall's reverberation time, a key parameter in determining the acoustic properties of a room (ISO 3382-1:2009). For this test, the handgun was set at a height of 1.5 meters. This impulse source would provide the needed signal-to-noise (S/N) ratio (Szlapa *et al.*, 2016). Measurements were taken from two positions on stage (handgun as source) and six positions (see Figure 15) in the auditorium seating area (sound level meter where listeners would normally be located). These were set at a height of 1.2 meters on a tripod and spaced at least half a wavelength apart (ISO 3382-1:2009) to avoid interference from reflecting surfaces. When firing, the sound level meter used, Type 2250 4G, measured peak levels and showed the decay curve, visually as approximately a straight line, as a function of time after the source had stopped (ISO 354:2003, 3.1). The reverberation time (RT) was measured using a T20 drop, then extrapolated to a 60dB range.

The results indicated that the reverberation times were excessive for speech performances and slightly high for piano solo performances (see Figure 16). This finding is crucial as it informs the need for adjustments in absorptive decoration to optimise the space for this potential use, providing a comprehensive assessment of the acoustic quality as a function of location within the hall.

Figure 15: Example of results of sound source 1, position 3

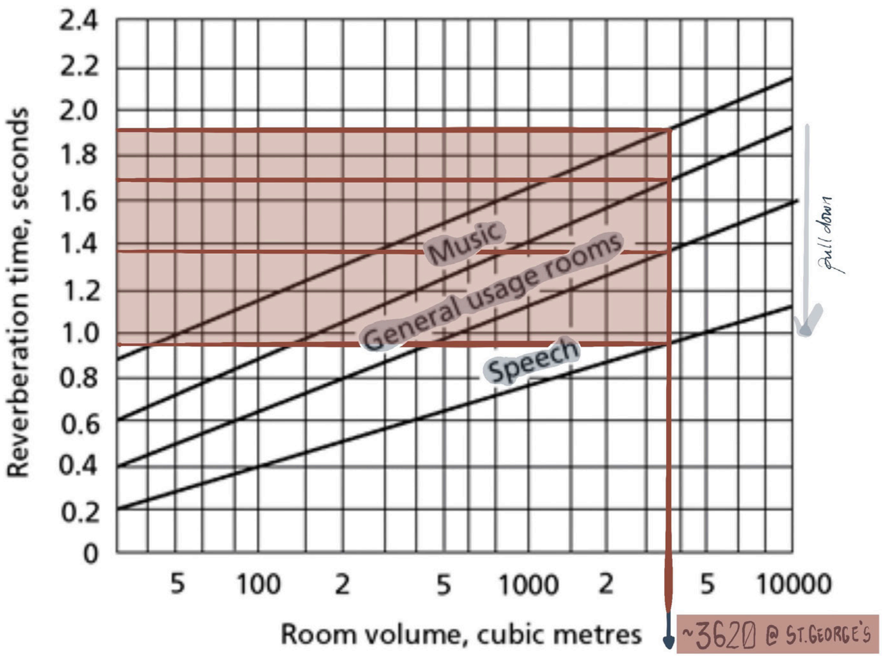

Figure 16: Reverberation time recommended depending on activity and volume of the room

The acoustic tests at St George’s concert hall generated valuable data on its current state. They indicated its potential for certain types of events, also leaving space for further proposals. These findings will guide the implementation of acoustic solutions to enhance the aesthetic appeal and the acoustic performance of this historic venue.

5.2 Interpretation from the validity of the tests and further proposals

While not a full DIRAC test, these methods provided essential data on the room's BNL with noise rating and RT. These tests revealed that adjustments could better suit various events. The focus is on reducing reverberation time by enhancing absorption, thus optimising the space for both piano solo performances and speech (see Figure 17), emphasising intelligibility (Acoustic Traffic LLC, 2019). It is important to note that while introducing modern alterations, the aim is to preserve the historical essence of the space in harmony with the extension by Patel Taylor Architects.

During multiple site visits and analyses, it became clear that adapting the space for speech performance was feasible, despite the high reverberation times revealed by the tests (detailed in Appendix A, Figure 3 and Figure 4). The reverberation time (shown at T20 in seconds), measured at 1.916 seconds via the gunshot test, is satisfactory for piano performances but excessive for speech (Brüel & Kjær, no date).

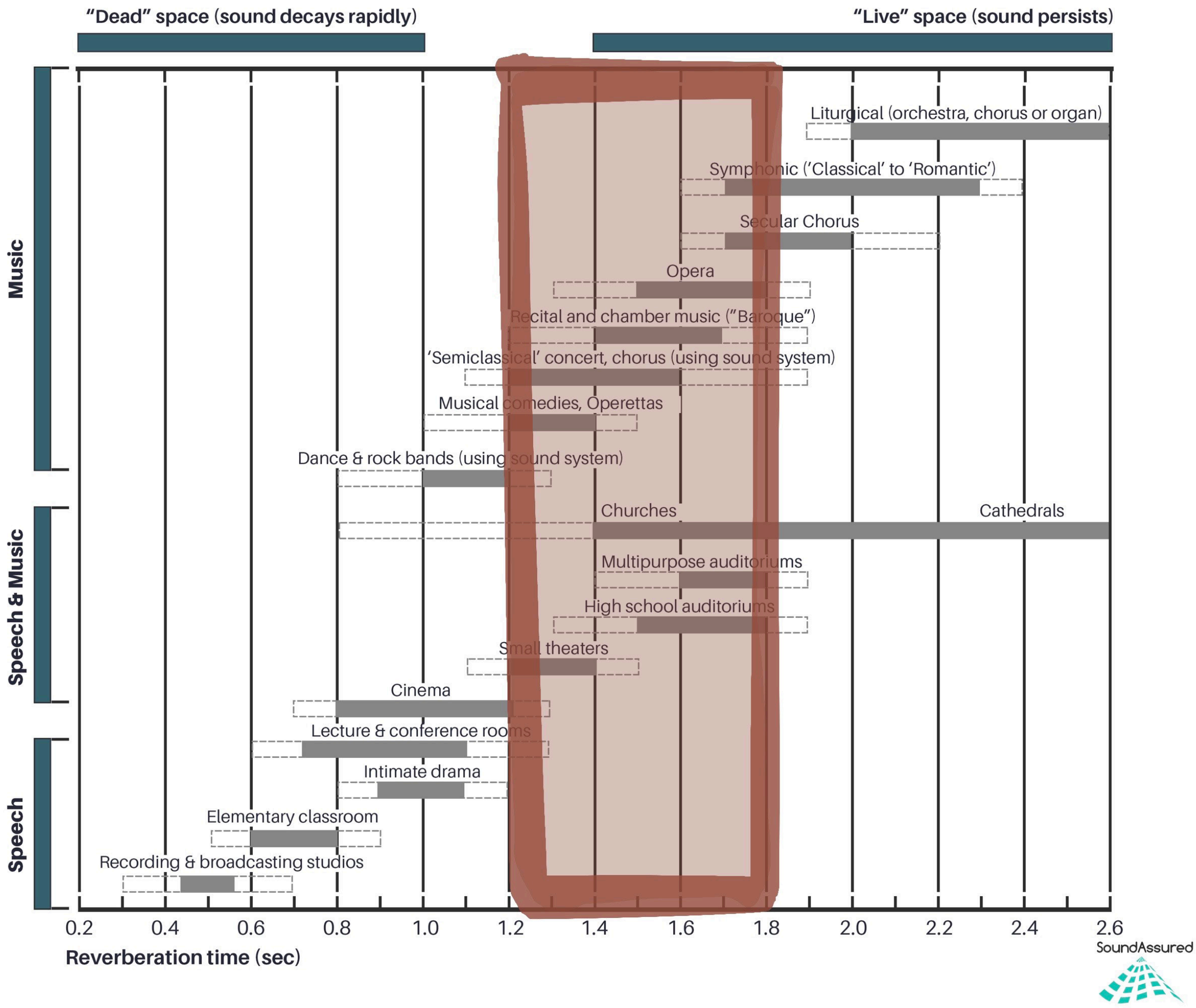

Figure 17: Reverberation time for music and speech in different spaces

To enhance speech intelligibility, the reverberation time obtained must be significantly reduced. This adjustment involves calculating the precise amount and placement of materials to achieve optimal acoustic conditions. It is crucial to consider that different manufacturers might offer materials with varying properties, such as insulation levels or innovative technologies, which would directly influence the material's absorption coefficient.

Sabine's formula was applied to St. George's room considering its volume and existing absorption to calculate total absorption (in Sabins) and improve speech performance. This calculation also determined the reverberation time, which varies at different frequencies due to the unique acoustic properties of the space. The existing absorption was 304.84 Sm^2, which required an absorption for spoken word performance to be 973.45 Sm^2. By this, the additional absorption needed was determined (see Appendix B).

Contributing to the acoustic properties of St. George's Bristol concert hall involved an exploration on various materials focused on targeting between 1 to 2 kHz frequency ranges and evaluating reverberation time (RT) peaks (Table 3 and detailed in Appendix A, Figure 3). The strategy involves using membrane or porous absorbers identifying their absorption coefficients (α) between 0 and 1, signifying the proportion of sound energy they absorb at specific frequencies, complemented by diffusers. These materials scatter sound waves in multiple directions and focus them towards specific areas in the rectangular, or "shoebox" concert hall. The selection process has considered the unique offerings of various manufacturers, including aspects like insulation, density, and air void, as well as the intended placement of these materials, whether on walls or ceilings. To achieve the additional absorption of 668.622 Sm^2 (see Appendix B) required for optimal speech intelligibility in this hall, a combination of materials in different areas have been proposed.

ACOUSTICS (sound absorption)	Type	Ø or Spacing	Open area	αw-class	NRC	1000Hz	2000Hz
WALLS							
	a) Acoustic plaster spray	N/A	N/A	0.90-A	0.90	0.95	1.00
	b) Linear wooden rib	12mm	24%	0.70-C	0.80	0.75	0.60
	c) Bespoke perforated panels	20mm	28%	0.5-D	0.65	0.50	0.45
CEILING							
	d) Microperforated panels (Nano)	0.5mm	5.9%	0.70-C	0.75	0.65	0.65

Table 3: Acoustic coefficients of chosen materials

Acoustic plaster with a 'monolithic' look will enhance the end walls. Acospray DC3 (Figure 18) has a weighted absorption coefficient of 1.0 (35mm), which significantly improves sound clarity and reduces reverberation (Stil Acoustics, 2020). It would be applied to the ends of opposing walls and above the stage, adding diffusive qualities through textured finishes (Figure 18 with mural). This approach scatters sound waves for even distribution and preserves the historical mural, blending new technologies with original aesthetics. The varied surface textures contribute both to acoustic performance and visual appeal. Additionally, the existing balconies, which already possess a base surface treatment, are further enhanced with vertical linear wooden ribs (Gustafs), adding acoustic and diffusive properties. These ribs will be colour matched to the original and the new extension's pale wood interior (Figure 19, left), ensuring aesthetic continuity and enhancing the overall user experience, as well offered by Charcoalblue Experience (2004). Furthermore, retractable wooden acoustic panels with bespoke perforation (Hush Panels, 2009) could replace the existing curtains at the sides of the stage, serving dual purposes of sound control and storage (see Appendix C). They would not only preserve the furniture but also add a professional aesthetic touch (Figure 20).

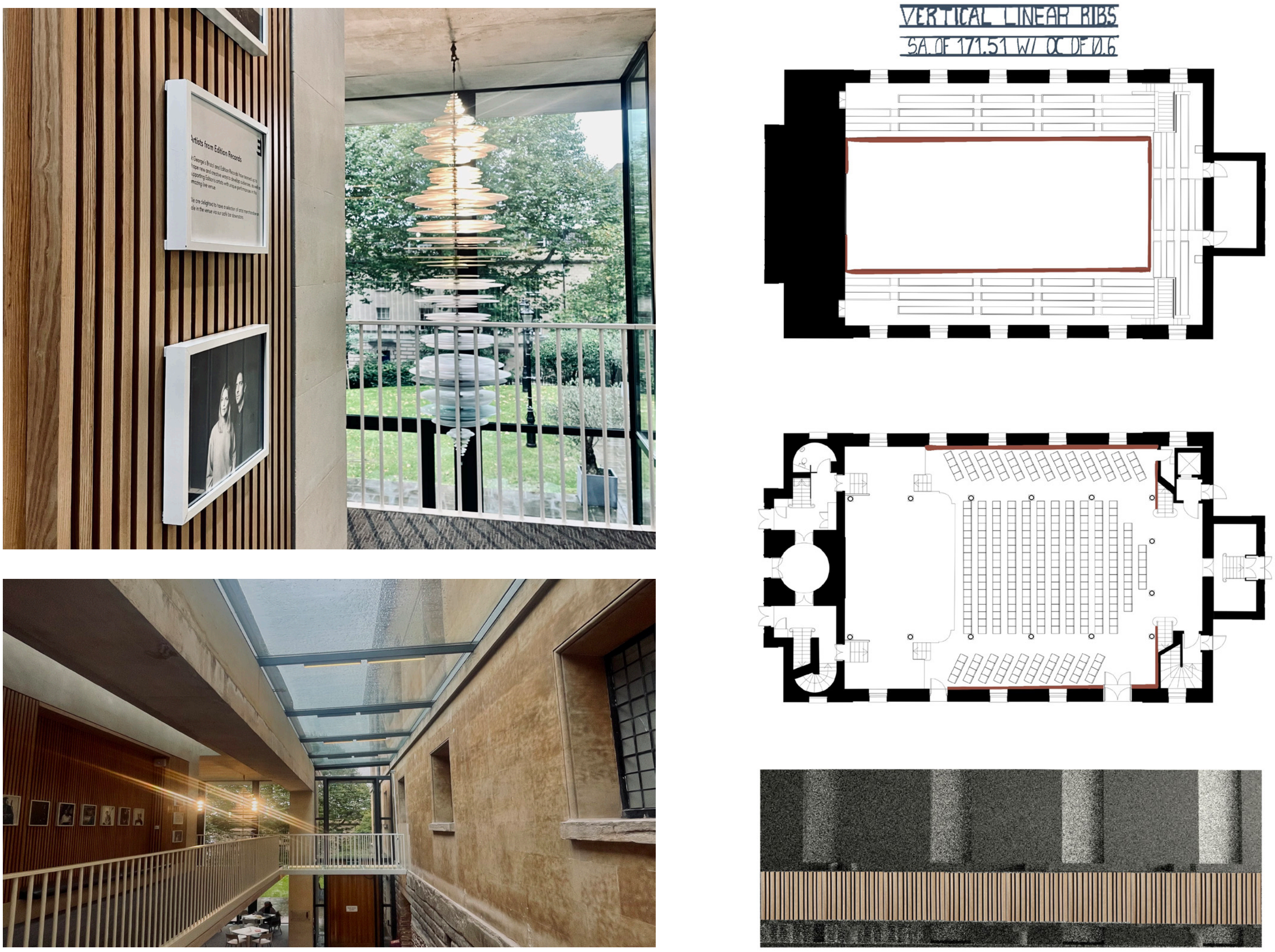

Figure 19: Linear wooden ribs (Gustafs, 2019) look and position in new extension (left) and in concert hall (right)

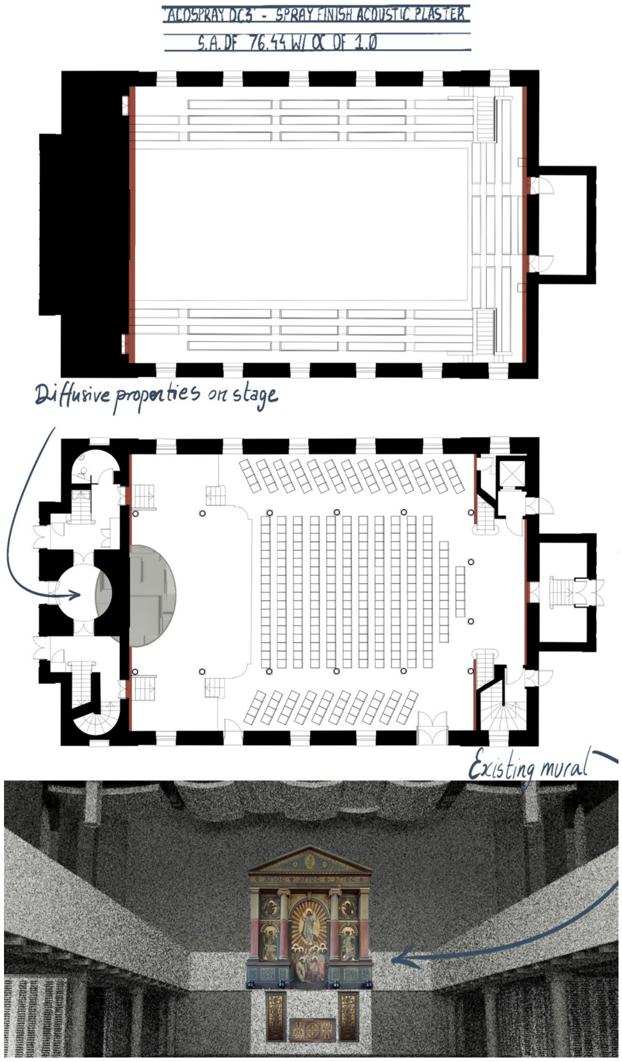

Figure 18: Acospray DC3 (Stil Acoustics, 2020) look and position

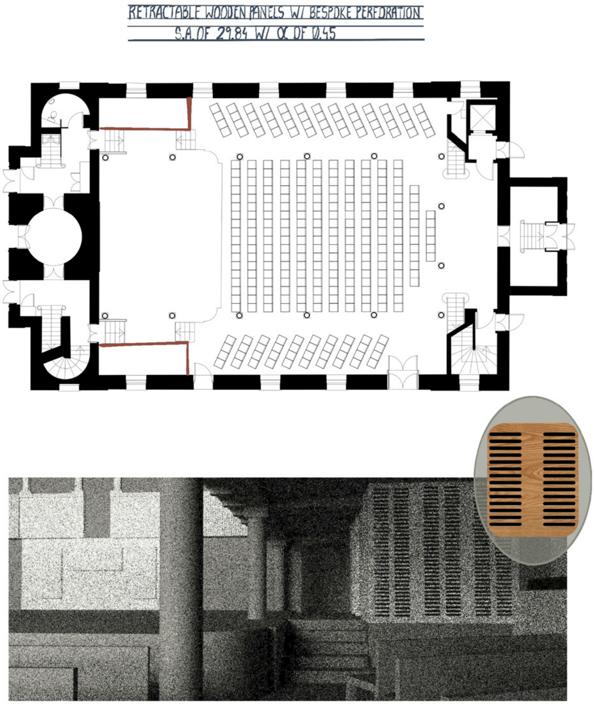

Figure 20: Wooden panels with bespoke perforation (Hush Panels, 2009) (QS slotted at Gustafs, 2019) look and position

Four sizes of suspended microperforated panels (Gustafs Nano solution, 2019), featuring both convex and concave designs, are proposed to cover the ceiling. The convex panels will aid in sound diffusion and even distribution, while the concave panels will focus sound on the audience. In conjunction with these panels, adjusting the lighting to complement the shapes and intensities of the suspended elements, and enhancing the stage and audience areas is suggested. Gustafs' specifications include 45mm of insulation and a 30mm air void (Hz/αp) for wall applications, and a similar insulation depth with a 200mm air void for the ceiling. However, the calculations have omitted them to be thinner and not dependent on insulation or air gaps (detailed in Appendix C, Figure 3). Importantly, all materials and integrations consider fire safety ratings appropriate for the space. The strategic addition of these materials contributes to a total absorption of 561.253 Sm^2, which falls short of the initially targeted additional absorption of 668.622 Sm^2 (see Appendix B). The presence of an audience (Appendix C, Figure 4), which varies depending on the performance, accounts for this discrepancy.

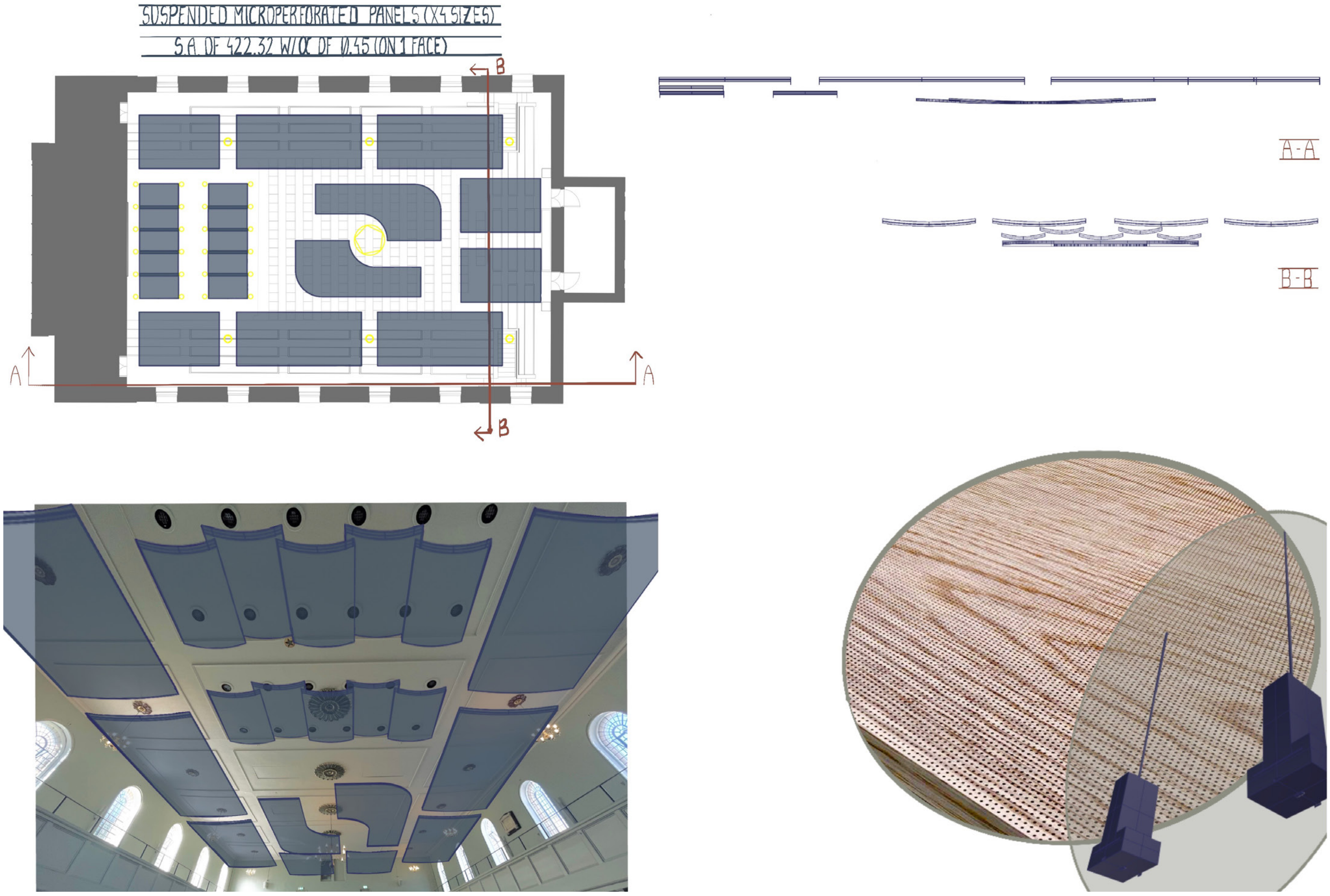

Figure 21: Wooden microperforated panels (Gustafs Nano solution, 2019) look and position

Looking ahead, the potential implementation of retractable or movable suspended microperforated panels, operated through acoustic software such as Rhino and Grasshopper with ‘plug-ins’ such as Pachyderm, would further engance the hall’s acoustic flexibility. Employing both theoretical reflection tests and practical computational design tools ensures that the decisions are grounded in both theoretical understanding and practical feasibility. This technological approach allows for precise and dynamic management in acoustics, catering to the specific needs of various events.

It is important to note that these proposals could have been made considering energy and cost efficiency, making them sustainable options for the long-term functioning of the concert hall. The material choices and designs aim to achieve a delicate balance between enhancing acoustic performance and maintaining the hall’s aesthetic integrity, thereby creating an acoustically optimised and visually appealing space (see Figure 22). While the current plan lays a solid foundation for acoustical enhancement, it is imperative to seek further professional input.

Figure 22: Light interplay

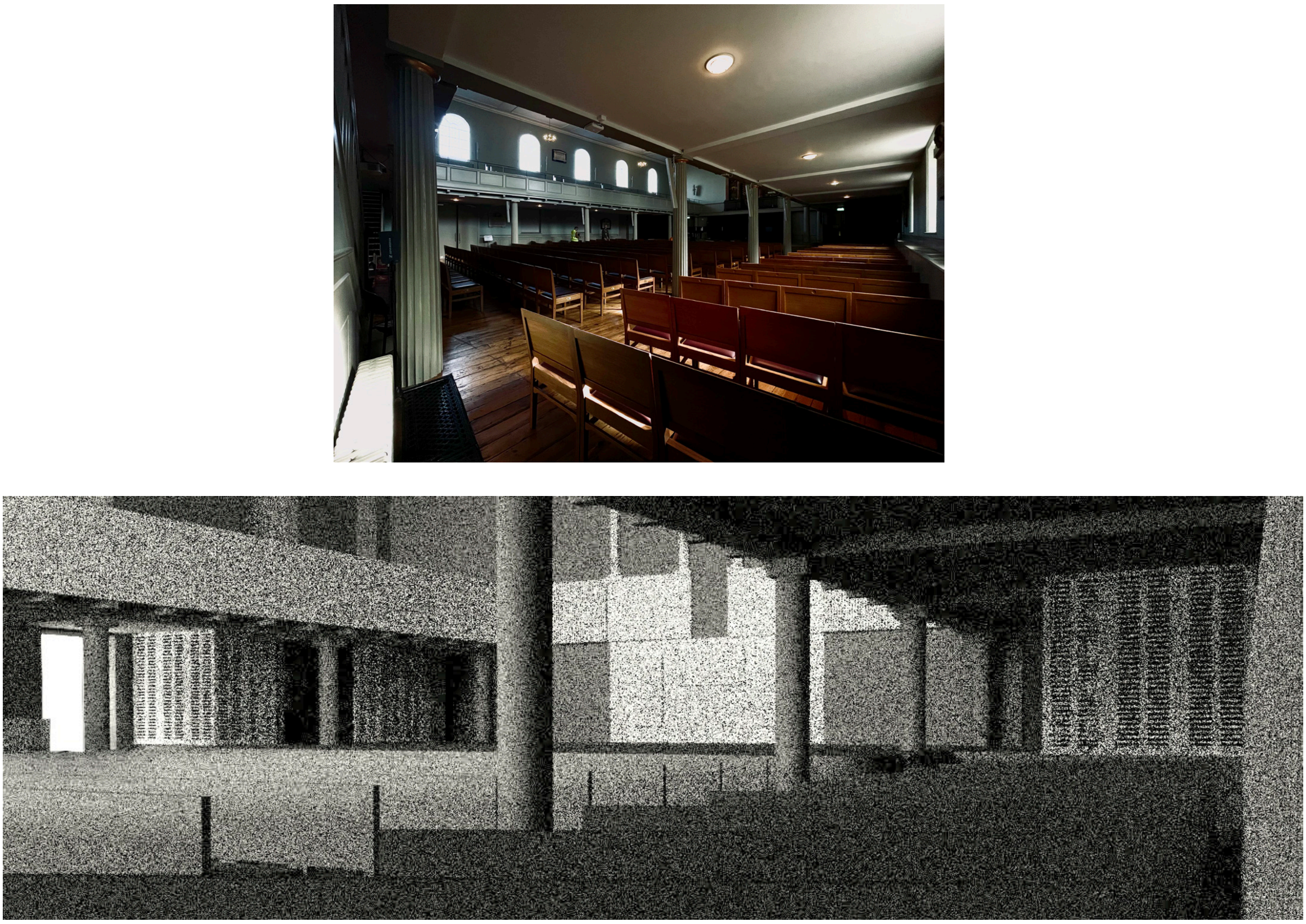

Figure 23: GF perspective original (top) and render (bottom)

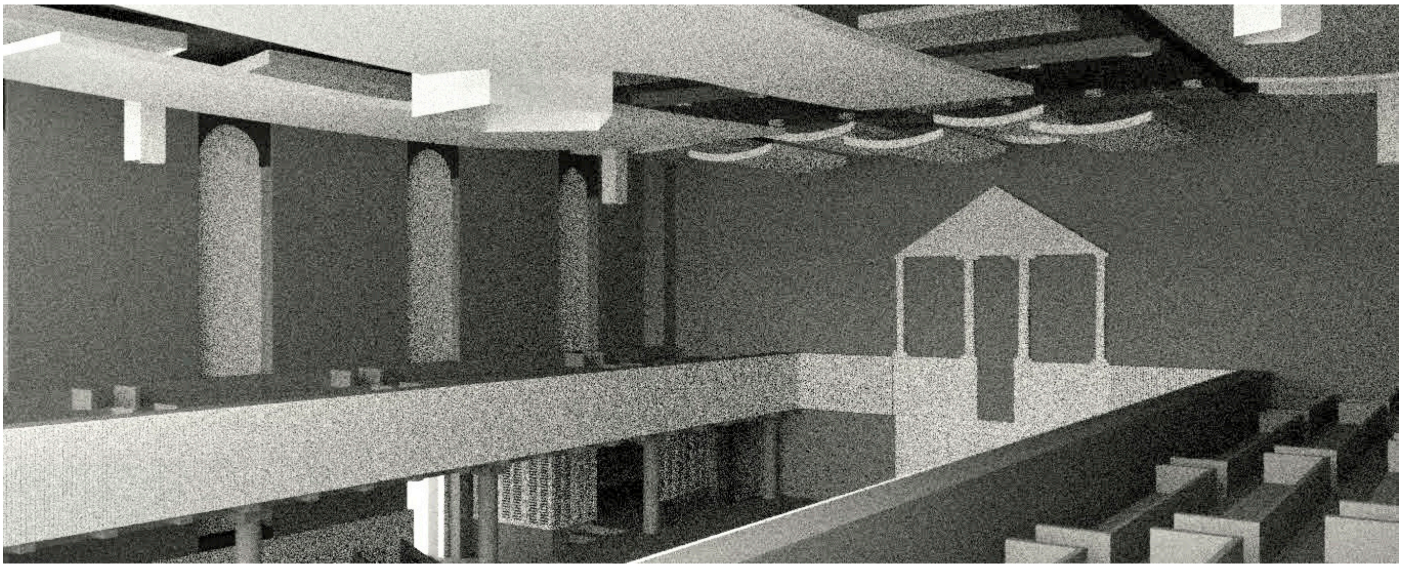

Figure 24: Perspective from balcony original (top) and render (bottom)

5.3 A concert at St. George's venue

During a recent event in the concert hall, ecmpirical data on the acoustic properties of the space were collected. It hosted a performance named Carmina Burana, featuring an orchestra on stage and a choir encompassing the entire perimeter of the main floor. The audience was situated on the balconies, presenting a distinctive auditory experience. This last prompted reflections on how future proposals might influence the hall's acoustics.

The welcome speech at the event, while audible, lacked the desired clarity, suggesting that the spoken word could benefit from the proposed modifications. In contrast, a piano solo introduction was highly pleasant to listen to. As these merged, a delay amongst them was accentuated. The percussion and wind instruments produced harsh sounds on the hall's surfaces, while the string instruments lacked clarity. This challenge could potentially be addressed with the placement of diffusive panels interplaying with absorptive qualities. The arrangement of the ranges of voices seemed to direct our ears towards specific areas of the space, resulting in a disorienting auditory experience initially. However, it was noted that the brain could adapt over time as the performance progressed.

Achieving a balanced acoustic environment would involve proposing modifications (see Figure 25) to enhance the clarity and distribution of sound for a variety of performances.

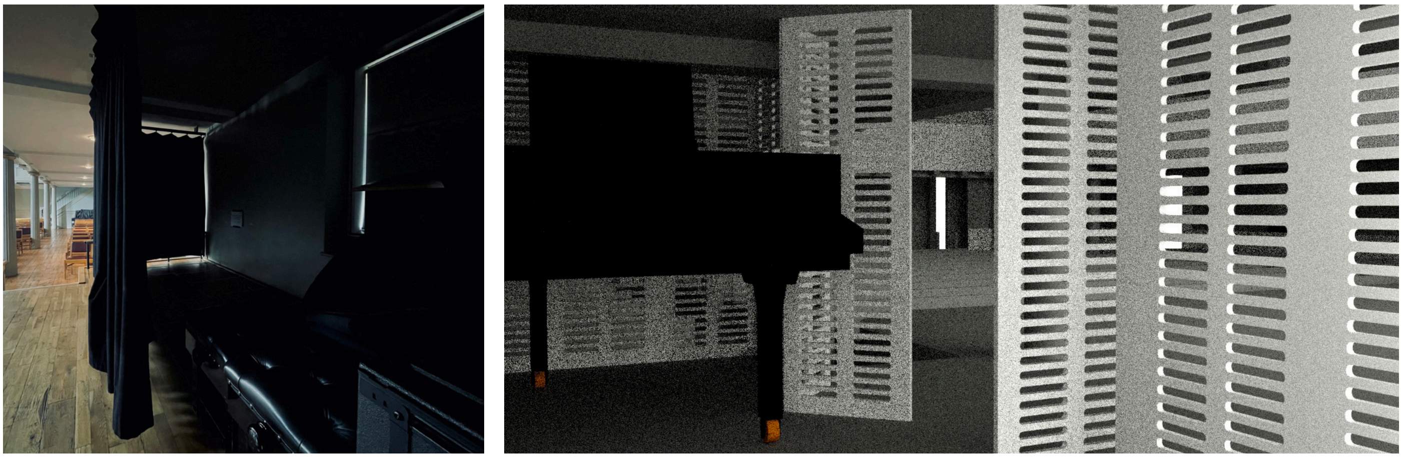

Figure 25: Stage sides (control and storage) proposal. Right side on original stage (left) and left side render on stage (right)

6. CONCLUSION

An exploration on the ‘musicalization’ of spaces (Prieto, 2009) through the case study of St. George’s Bristol has demonstrated how dynamic structures and rhythms profoundly influence the orchestration of architecture and acoustics. Reverberation, particularly in shoebox concert halls, plays a crucial role in enriching the musical experience by amplifying low and high frequencies (Lokki *et al.*, 2015), a fact underscored by Sir Simon Rattle’s acclaim of ‘St. George’s acoustic excellence’ (St. George’s Bristol, 2024). Our findings reveal that while the current noise levels are well below its recommendations and the space ideally resonates with piano performances, adjustments like reducing reverberation time and integrating absorptive properties are essential, for example, for speech intelligibility. The background noise level test confirms the effective mitigation of sound interference from adjacent areas like the café-bar, particularly the low frequencies intruding into the concert hall space, thereby exemplifying a thoughtful acoustic design. Underscoring a holistic approach to architectural acoustics, one that not only adheres to Vitruvius’ ancient principles but is also propelled by computational design, this research contributes to spaces that are not just seen but deeply heard and resonated with, echoing a harmony between the past and the present in every architectural note.

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8. APPENDICES

8.1 Appendix A. Data Analysis

- Setup details

SETUP DETAILS								
Project Name	Creation Time	Application	[System] Instrument Type	[Transducer] Micr Used	[Transducer] Transd Descr	[Calibration] CalibrationTime UTC Date	[Calibration] CalibrationTim eUTC Time	[Bandwidth] Bandwidth
Project 043	27/10/2023	BZ7227 Version 4.7.5	Type2250	4189(2984023)	Free-field 1/2"	############	GMT Standard Time	1/3-octave

Figure 1: Setup details at St. George's Bristol concert hall

- Background noise

BACKGROUND NOISE										
Project Name	Elapsed Time	LZeq 12.5Hz	LZeq 16Hz	LZeq 20Hz	LZeq 25Hz	LZeq 31.5Hz	LZeq 40Hz	LZeq 50Hz	LZeq 63Hz	LZeq 80Hz
St Georges background noise - Project 044	00:00:31	37,24	32,48	37,68	41,25	38,31	31,15	30,81	28,13	26,75
		LZeq 100Hz	LZeq 125Hz	LZeq 160Hz	LZeq 200Hz	LZeq 250Hz	LZeq 315Hz	LZeq 400Hz	LZeq 500Hz	LZeq 630Hz
		28,27	24,2	15,27	15,01	17,04	12,93	15,29	18,08	15,29
		LZeq 800Hz	LZeq 1kHz	LZeq 1.25kHz	LZeq 1.6kHz	LZeq 2kHz	LZeq 2.5kHz	LZeq 3.15kHz	LZeq 4kHz	LZeq 5kHz
		13,88	15,22	13,53	13,04	10,19	10,11	8,42	7,85	8,06
		LZeq 6.3kHz	LZeq 8kHz	LZeq 10kHz	LZeq 12.5kHz	LZeq 16kHz	LZeq 20kHz			
		8,35	8,22	8,04	7,73	7,53	9,29			
Blue denotes octave bands used for Noise Rating calc										

Room Rating = 16

From https://www.engineeringtoolbox.com/nr-noise-rating-d_518.html

Frequency (Hz)	Avg. BNL (dB)	A-weighting correction (dB)	BNL dB(A)
16	32,5	-56,7	-24,2
32	38,3	-39,4	-1,1
63	28,1	-26,2	1,9
125	24,2	-16,1	8,1
250	17,0	-8,6	8,4
500	18,1	-3,2	14,9
1000	15,2	0	15,2
2000	10,2	1,2	11,4
4000	7,9	1	8,9
8000	8,2	-1,1	7,1
16000	7,5	-6,6	0,9
	40	**dB**	**20**

Figure 2: Background noise octave bands for calculations (The Engineering ToolBox, 2003)

- Reverberation Time

REVERBERATION TIME

Project Name	Position	Excluded	Elapsed Time
Project 043	Pos 01	0	00:00:06

T20 100Hz	T20 125Hz	T20 160Hz	T20 200Hz	T20 250Hz	T20 315Hz	T20 400Hz	T20 500Hz	T20 630Hz	T20 800Hz	T20 1kHz	T20 1.25kHz	T20 1.6kHz	T20 2kHz
1,27	1,47	1,47	1,72	1,72	1,59	1,75	2,24	2,04	2,28	2,26	2,37	2,51	2,35
T20 2.5kHz	T20 3.15kH	T20 4kHz	T20 5kHz	T30 100Hz	T30 125Hz	T30 160Hz	T30 200Hz	T30 250Hz	T30 315Hz	T30 400Hz	T30 500Hz	T30 630Hz	T30 800Hz
2,26	2,18	1,98	1,72	1,21	1,39	1,38	1,65	1,6	1,69	2,04	2,17	2,17	2,3
T30 1kHz	T30 1.25kH	T30 1.6kHz	T30 2kHz	T30 2.5kHz	T30 3.15kHz	T30 4kHz	T30 5kHz	EDT 100Hz	EDT 125Hz	EDT 160Hz	EDT 200Hz	EDT 250Hz	EDT 315Hz
2,37	2,4	2,44	2,36	2,31	2,17	2,02	1,75	1,15	1,04	0,87	0,97	1,05	1,17
EDT 400Hz	EDT 500Hz	EDT 630Hz	EDT 800Hz	EDT 1kHz	EDT 1.25kHz	EDT 1.6kHz	EDT 2kHz	EDT 2.5kHz	EDT 3.15kHz	EDT 4kHz	EDT 5kHz		
1,82	2,13	1,72	2,44	2,29	2,32	2,14	2,07	2,01	2	1,99	1,53		

Project Name	Position	Excluded	Elapsed Time
Project 043	Pos 02	0	00:00:06

T20 100Hz	T20 125Hz	T20 160Hz	T20 200Hz	T20 250Hz	T20 315Hz	T20 400Hz	T20 500Hz	T20 630Hz	T20 800Hz	T20 1kHz	T20 1.25kHz	T20 1.6kHz	T20 2kHz
0,89	1,07	1,21	1,79	1,5	1,73	1,89	2,08	1,99	2,42	2,37	2,37	2,45	2,31
T20 2.5kHz	T20 3.15kH	T20 4kHz	T20 5kHz	T30 100Hz	T30 125Hz	T30 160Hz	T30 200Hz	T30 250Hz	T30 315Hz	T30 400Hz	T30 500Hz	T30 630Hz	T30 800Hz
2,14	2,11	1,85	1,73	1,06	1,33	1,36	1,81	1,66	1,81	2,01	2,05	2,13	2,34
T30 1kHz	T30 1.25kH	T30 1.6kHz	T30 2kHz	T30 2.5kHz	T30 3.15kHz	T30 4kHz	T30 5kHz	EDT 100Hz	EDT 125Hz	EDT 160Hz	EDT 200Hz	EDT 250Hz	EDT 315Hz
2,4	2,41	2,4	2,37	2,24	2,15	1,94	1,72	1,53	1,5	1,41	1,46	1,56	1,02
EDT 400Hz	EDT 500Hz	EDT 630Hz	EDT 800Hz	EDT 1kHz	EDT 1.25kHz	EDT 1.6kHz	EDT 2kHz	EDT 2.5kHz	EDT 3.15kHz	EDT 4kHz	EDT 5kHz		
1,44	2,14	1,97	2,26	1,94	1,86	1,93	2,3	1,97	1,86	1,98	1,67		

Project Name	Position	Excluded	Elapsed Time
Project 043	Pos 03	0	00:00:06

T20 100Hz	T20 125Hz	T20 160Hz	T20 200Hz	T20 250Hz	T20 315Hz	T20 400Hz	T20 500Hz	T20 630Hz	T20 800Hz	T20 1kHz	T20 1.25kHz	T20 1.6kHz	T20 2kHz
1,05	1,3	1,2	1,5	1,77	1,79	1,75	2,04	2,27	2,31	2,44	2,33	2,43	2,31
T20 2.5kHz	T20 3.15kH	T20 4kHz	T20 5kHz	T30 100Hz	T30 125Hz	T30 160Hz	T30 200Hz	T30 250Hz	T30 315Hz	T30 400Hz	T30 500Hz	T30 630Hz	T30 800Hz
2,23	2,19	1,99	1,7	1,13	1,51	1,38	2,03	1,9	2,02	1,91	2,13	2,34	2,31
T30 1kHz	T30 1.25kH	T30 1.6kHz	T30 2kHz	T30 2.5kHz	T30 3.15kHz	T30 4kHz	T30 5kHz	EDT 100Hz	EDT 125Hz	EDT 160Hz	EDT 200Hz	EDT 250Hz	EDT 315Hz
2,38	2,38	2,38	2,35	2,28	2,18	1,99	1,74	0,89	1,02	1,02	1,01	1,64	1,05
EDT 400Hz	EDT 500Hz	EDT 630Hz	EDT 800Hz	EDT 1kHz	EDT 1.25kHz	EDT 1.6kHz	EDT 2kHz	EDT 2.5kHz	EDT 3.15kHz	EDT 4kHz	EDT 5kHz		
1,87	1,53	1,52	2,06	1,99	1,73	2,44	2,21	2,17	1,99	1,81	1,63		

Project Name	Position	Excluded	Elapsed Time
Project 043	Pos 04	0	00:00:06

T20 100Hz	T20 125Hz	T20 160Hz	T20 200Hz	T20 250Hz	T20 315Hz	T20 400Hz	T20 500Hz	T20 630Hz	T20 800Hz	T20 1kHz	T20 1.25kHz	T20 1.6kHz	T20 2kHz
1,55	1,41	1,73	2,03	1,57	1,52	1,98	2,1	2,04	2,08	2,28	2,24	2,29	2,42
T20 2.5kHz	T20 3.15kH	T20 4kHz	T20 5kHz	T30 100Hz	T30 125Hz	T30 160Hz	T30 200Hz	T30 250Hz	T30 315Hz	T30 400Hz	T30 500Hz	T30 630Hz	T30 800Hz
2,19	2,1	2,03	1,74	1,59	1,24	1,43	1,8	1,64	1,84	2,27	2,15	2,18	2,26
T30 1kHz	T30 1.25kH	T30 1.6kHz	T30 2kHz	T30 2.5kHz	T30 3.15kHz	T30 4kHz	T30 5kHz	EDT 100Hz	EDT 125Hz	EDT 160Hz	EDT 200Hz	EDT 250Hz	EDT 315Hz
2,41	2,39	2,38	2,44	2,29	2,18	2,05	1,76	1,53	0,93	0,63	1,18	1,44	1,24
EDT 400Hz	EDT 500Hz	EDT 630Hz	EDT 800Hz	EDT 1kHz	EDT 1.25kHz	EDT 1.6kHz	EDT 2kHz	EDT 2.5kHz	EDT 3.15kHz	EDT 4kHz	EDT 5kHz		
1,48	1,71	1,68	2,15	2,37	1,99	2,2	2,16	2,1	2,04	1,83	1,44		

Project Name	Position	Excluded	Elapsed Time
Project 043	Pos 05	0	00:00:06

T20 100Hz	T20 125Hz	T20 160Hz	T20 200Hz	T20 250Hz	T20 315Hz	T20 400Hz	T20 500Hz	T20 630Hz	T20 800Hz	T20 1kHz	T20 1.25kHz	T20 1.6kHz	T20 2kHz
0,91	0,98	1,03	1,57	1,43	1,67	2	2,09	2,17	2,22	2,4	2,2	2,35	2,28
T20 2.5kHz	T20 3.15kH	T20 4kHz	T20 5kHz	T30 100Hz	T30 125Hz	T30 160Hz	T30 200Hz	T30 250Hz	T30 315Hz	T30 400Hz	T30 500Hz	T30 630Hz	T30 800Hz
2,29	2,18	2,07	1,74	1,24	1,04	1,32	1,6	1,63	1,71	2,05	2,19	2,19	2,31
T30 1kHz	T30 1.25kH	T30 1.6kHz	T30 2kHz	T30 2.5kHz	T30 3.15kHz	T30 4kHz	T30 5kHz	EDT 100Hz	EDT 125Hz	EDT 160Hz	EDT 200Hz	EDT 250Hz	EDT 315Hz
2,41	2,33	2,4	2,36	2,36	2,2	2,06	1,78	1,14	1,2	0,89	1,34	1,23	1,37
EDT 400Hz	EDT 500Hz	EDT 630Hz	EDT 800Hz	EDT 1kHz	EDT 1.25kHz	EDT 1.6kHz	EDT 2kHz	EDT 2.5kHz	EDT 3.15kHz	EDT 4kHz	EDT 5kHz		
1,56	1,44	1,64	2,19	2,1	2,25	2,2	2,22	1,87	2,05	1,8	1,51		

Project Name	Position	Excluded	Elapsed Time
Project 043	Pos 06	0	00:00:06

T20 100Hz	T20 125Hz	T20 160Hz	T20 200Hz	T20 250Hz	T20 315Hz	T20 400Hz	T20 500Hz	T20 630Hz	T20 800Hz	T20 1kHz	T20 1.25kHz	T20 1.6kHz	T20 2kHz
1,12	1,29	1,66	1,77	1,46	1,66	1,77	1,78	2,05	2,26	2,31	2,31	2,38	2,31
T20 2.5kHz	T20 3.15kH	T20 4kHz	T20 5kHz	T30 100Hz	T30 125Hz	T30 160Hz	T30 200Hz	T30 250Hz	T30 315Hz	T30 400Hz	T30 500Hz	T30 630Hz	T30 800Hz
2,31	2,15	1,98	1,73	1,15	1,22	1,59	1,7	1,58	1,75	2,01	2,08	2,16	2,24
T30 1kHz	T30 1.25kH	T30 1.6kHz	T30 2kHz	T30 2.5kHz	T30 3.15kHz	T30 4kHz	T30 5kHz	EDT 100Hz	EDT 125Hz	EDT 160Hz	EDT 200Hz	EDT 250Hz	EDT 315Hz
2,37	2,32	2,37	2,37	2,29	2,15	2,03	1,75	0,65	0,93	0,93	1,22	1,51	1,14
EDT 400Hz	EDT 500Hz	EDT 630Hz	EDT 800Hz	EDT 1kHz	EDT 1.25kHz	EDT 1.6kHz	EDT 2kHz	EDT 2.5kHz	EDT 3.15kHz	EDT 4kHz	EDT 5kHz		
1,53	1,94	1,61	2,11	1,97	2,12	2,13	2,09	2,11	1,98	1,81	1,49		

Figure 3: Source 1 with Positions 1, 2 and 3 and Source 2 with positions 4, 5 and 6

Project 043	Pos 03 Pos 04 Pos 05 Pos 06	2,24	1,06	1,23	1,36	1,72	1,54	1,64	1,83	2,05	2,07	2,26
		T20 Room 1kHz	T20 Room 1.25kHz	T20 Room 1.6kHz	T20 Room 2kHz	T20 Room 2.5kHz	T20 Room 3.15kHz	T20 Room 4kHz	T20 Room 5kHz	T30 (500 Hz-2 kHz)	T30 Room 100Hz	T30 Room 125Hz
		2,31	2,29	2,4	2,32	2,24	2,15	1,98	1,72	2,3	1,23	1,3
		T30 Room 160Hz	T30 Room 200Hz	T30 Room 250Hz	T30 Room 315Hz	T30 Room 400Hz	T30 Room 500Hz	T30 Room 630Hz	T30 Room 800Hz	T30 Room 1kHz	T30 Room 1.25kHz	T30 Room 1.6kHz
		1,4	1,75	1,66	1,79	2,06	2,12	2,19	2,3	2,38	2,36	2,39
		T30 Room 2kHz	T30 Room 2.5kHz	T30 Room 3.15kHz	T30 Room 4kHz	T30 Room 5kHz	EDT (500 Hz-2 kHz)	EDT Room 100Hz	EDT Room 125Hz	EDT Room 160Hz	EDT Room 200Hz	EDT Room 250Hz
		2,38	2,3	2,17	2,01	1,75	2,02	1,21	1,18	0,94	1,18	1,44
		EDT Room 315Hz	EDT Room 400Hz	EDT Room 500Hz	EDT Room 630Hz	EDT Room 800Hz	EDT Room 1kHz	EDT Room 1.25kHz	EDT Room 1.6kHz	EDT Room 2kHz	EDT Room 2.5kHz	EDT Room 3.15kHz
		1,19	1,64	1,82	1,67	2,14	2,15	2,08	2,17	2,14	2	1,93
		EDT Room 4kHz	EDT Room 5kHz									
		1,84	1,52									
Blue denotes evaluated measurements												

Figure 4: RT for concert hall (measurements, total reverberation times and Sabine formula)

Total reverberation times		
T20 for room =	1,916315789	
T30 for room =	1,991578947	
EDT (Early decay time)	1,697894737	
T60 Reverb time predicted by Sabine formula =	1,788888889	
Length of room =	10	m
Depth of room =	10	m
Breadth of room =	10	m
Area of chosen absorber added	100	m2
Absorbtion coefficient of chosen absorber =	0,9	Sabines

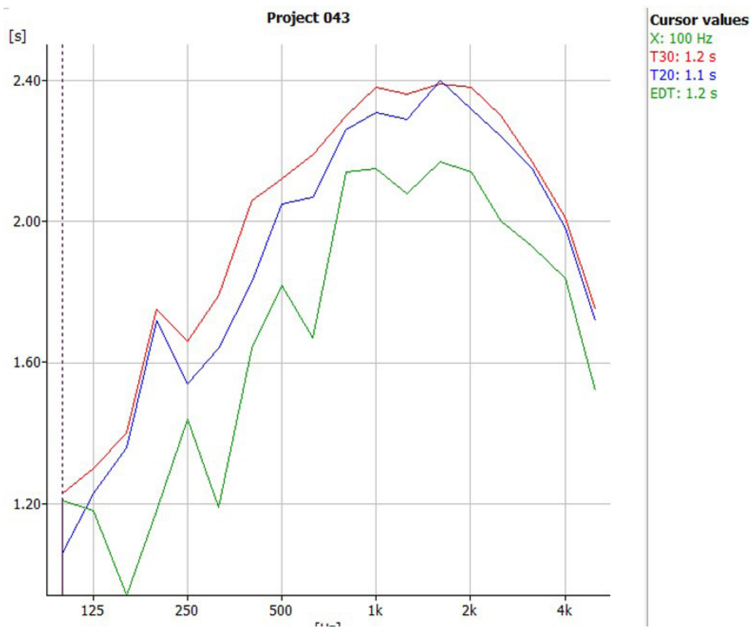


Figure 5: RT values for concert hall

8.2 Appendix B. Formulas and Calculations

Result of gunshot test:

RT = T20 = 1.916 seconds

This is fine **for piano solo** (if a little high) (Acoustic Traffic LLC, 2019). **Spoken word RT (T20) should = 0.6 seconds** to maximise speech intelligibility (Commercial Acoustics, 2017).

How much absorption must be added to give a speech performance?

Sabine formula: ***RT = 0.161·V /At*** where:

RT is the reverberation time (seconds);

V is the volume of the room (m^2); and

At is the total absorption in the room (S(Sabins)m^2).

Finding the current absorption of St. George's:

At = 0.161·V / RT

= 0.161 ((24.64)(17.14)(8.59)) / 1.916

= **304.84 Sm²**

How much absorption would you need for a spoken word performance?

At = 0.161 ((24.64)(17.14)(8.59)) / 0.6

= **973.46 Sm²**

How much absorption do we need to add?

Aadditional = Anew – Aoriginal

Aadditional = 973.46 - 304.84

= **668.622 Sm²**

What amount of material must be added?

RT is greatest at 1 to 2 kHz so that must be targeted with membrane or porous absorbers (Elvidge, 2023). These will be backed up with some diffusers, being able to both scatter sound waves in multiple directions and/or enhance the clarity and definition by focusing sound waves toward specific areas of the rectangular, or "shoebox" concert hall.

Aadditional = SA · α where:

Aadditional is the additional absorption area (m^2);

SA is the surface area of the material in the room (m^2); and

α is the absorption coefficient of the material (value between 0 and 1).

MATERIALS USED (See Appendix C):

We want to reach an **additional absorption of 668.622 Sm²**

We will use the following expression to reach this number:

Aadditional = SA · α

The materials added will cover certain walls and the ceiling, adapted to the specific space (St. George's Concert Hall).

Walls:

Apart from normal white paint (for a better aesthetic look only), **monolithic acoustic plaster** (Stil Acoustics, 2020)

Aadditional opposite stage= 76.44 · 1.0 = **76.44 Sm²**

Aadditional stage wall= 93.971 · 1.0 = **93.971 Sm²**

Detail:

Diffusion added to the wall on stage (93.971 Sm²)

Linear wooden rib (Gustafs, 2019)

Aadditional = 171.51 · 0.60 = **102.906 Sm²**

Retractable **wooden acoustic panels bespoke perforation** (Hush Panels, 2009 and QS slotted at Gustafs, 2019)

Aadditional =29.84 · 0.45 = **13.428 Sm²**

Ceiling:

4 sizes of **wooden microperforated panels** (Gustafs Nano solution, 2019)

Aadditional = 422.32 · 0.65 = **274.508 Sm²**

Combination of convex and concave panels

The addition of these, 561.253 Sm², is clearly below the additional absorption we needed to add (668.622 Sm²). This is because the occupation of people would fill up the rest of the absorption and the desired Sm² would be reached, perhaps making this place optimal both for speech and piano solo performances.

8.3 Appendix C. Sound Absorption Coefficients

The most popular one coat system.

1.1 Acospray DC3 datasheet

The most popular spray finish, DC3 offers excellent acoustic control with an even, coarse texture. Different thicknesses affect the acoustic performance and installation time, and the material can be coloured to suit the project.

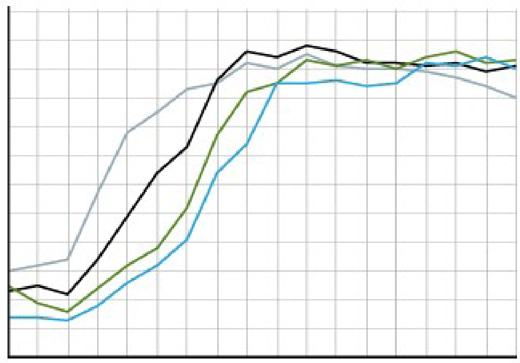
Key Features

Fast installation
Covers imperfections
High sound absorption
High recycled content
Cost effective
Can be patch repaired
Colour matching
Applies to uneven surfaces

Fire performance

EN 13501-1:2007+A1:2009 B-s1.d0. European equivalent to BS 476: Part 6 & 7 Class O.

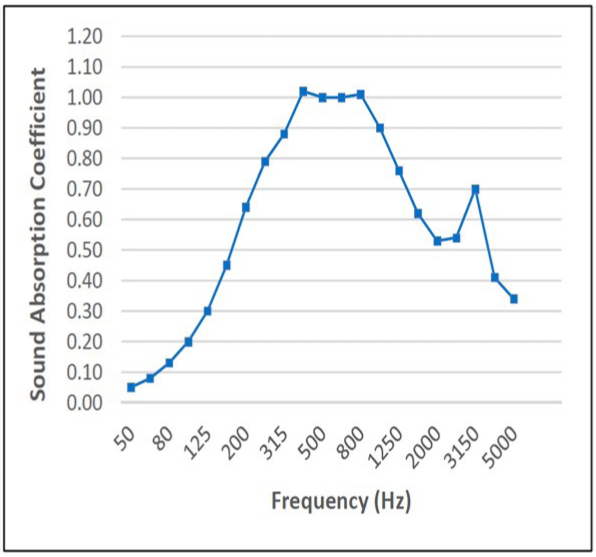
Acospray DC3 absorption (354: 2003)



Build up	α_w	NRC	Class	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
15mm	0,55	0,70	D	0,15	0,25	0,65	0,95	0,95	1,00
20mm	0,60	0,80	C	0,20	0,30	0,75	1,00	1,00	1,00
25mm	0,75	0,85	B	0,25	0,50	0,90	1,00	1,00	1,00
35mm	1.00	0,95	A	0,30	0,75	1,00	1,00	1,00	0,95

Figure 1: Acospray DC3 absorption coefficients (Stil Acoustics, 2020)

Frequency (Hz)	alpha random	
50	0.05	
63	0.08	
80	0.13	
100	0.20	
125	0.30	0.30
160	0.45	
200	0.64	
250	0.79	0.75
315	0.88	
400	1.02	
500	1.00	1.00
630	1.00	
800	1.01	
1000	0.90	0.90
1250	0.76	
1600	0.62	
2000	0.53	0.55
2500	0.54	
3150	0.70	
4000	0.41	0.50
5000	0.34	



NRC 0.80

Open Space: 23%

Figure 2: Wooden panels, bespoke perforation absorption coefficients (Hush Panels, 2009)

Gustafs Acoustic Values

ACOUSTICS	Typ	Ø or Spacing	Slott (D)	cc (A/E)	Open area	WALL: 45 mm insulation + 30 mm air void (Hz/αp)								CEILING: 45 mm insulation + 200 mm air void (Hz/αp)							
						αw	NRC	125	250	500	1000	2000	4000	αw	NRC	125	250	500	1000	2000	4000
Sound absorption	Plain	-	-	-	-	-	-	0,10	0,05	0,05	0,05	0,05	0,05	-	-	0,20	0,10	0,05	0,05	0,05	0,05
	Nano	0,5 mm	-	1,75/2	5,9%	0,80-B	0,90	0,35	0,90	1,00	0,90	0,75	0,65	0,85-B	0,90	0,45	0,95	0,90	0,90	0,80	0,70
	Nano*	0,5 mm	-	1,75/2	5,9%	-	-	-	-	-	-	-	-	0,70-C	0,75	0,40	0,80	0,85	0,65	0,65	0,60
	PH5	5 mm	-	20/20	5 %	0,30-D	0,50	0,50	0,70	0,65	0,45	0,25	0,20	0,35-D	0,50	0,50	0,65	0,55	0,45	0,30	0,20
	PH8	8 mm	-	20/20	12 %	0,55-D	0,80	0,35	0,85	1,00	0,75	0,55	0,40	0,55-D	0,80	0,65	0,95	0,85	0,80	0,55	0,40
	PH8-F	8 mm	-	20/20	12%	0,60-C	0,85	0,35	0,85	0,95	1,00	0,50	0,35	0,60-C	0,85	0,55	0,90	0,95	1,00	0,60	0,35
	PH10	10 mm	-	20/20	18 %	0,70-C	0,85	0,35	0,85	1,00	0,90	0,70	0,55	0,75-C	0,90	0,65	1,00	0,90	0,85	0,75	0,60
	PG5	5 mm	-	20/20	3 %	0,25-E	0,40	0,40	0,50	0,45	0,35	0,20	0,15	0,30-D	0,40	0,45	0,45	0,40	0,40	0,25	0,15
	PG8	8 mm	-	20/20	8 %	0,45-D	0,65	0,40	0,85	0,80	0,60	0,40	0,30	0,50-D	0,65	0,55	0,75	0,70	0,65	0,40	0,35
	PS2	3 mm	-	20/20	2 %	0,20-E	0,50	0,30	0,85	0,70	0,30	0,15	0,05	0,25-E	0,45	0,55	0,70	0,55	0,35	0,20	0,10
	PD8	8 mm	-	10/10	24 %	0,80-B	0,90	0,30	0,80	1,00	0,95	0,75	0,65	0,85-B	0,90	0,65	1,00	0,95	0,90	0,80	0,70
	SM5	5 mm	20 mm	20/20	15 %	0,65-C	0,80	0,30	0,75	1,00	0,80	0,60	0,50	0,65-C	0,75	0,50	0,75	0,80	0,75	0,65	0,50
	SM8	8 mm	20 mm	20/20	26 %	0,85-B	0,85	0,30	0,75	1,00	0,90	0,80	0,70	0,85-B	0,85	0,50	0,80	0,90	0,85	0,85	0,75
	SH5	5 mm	40 mm	20/30	15 %	0,60-C	0,80	0,35	0,80	1,00	0,80	0,60	0,45	0,60-C	0,80	0,65	0,95	0,85	0,80	0,60	0,45
	SH8	8 mm	40 mm	20/30	26 %	0,75-C	0,85	0,35	0,80	1,00	0,95	0,70	0,60	0,75-C	0,90	0,65	1,00	0,95	0,90	0,75	0,60
	SG5	5 mm	55 mm	20/30	12 %	0,50-D	0,75	0,35	0,90	0,95	0,70	0,50	0,35	0,55-D	0,70	0,55	0,85	0,80	0,70	0,50	0,40
	SG8	8 mm	55 mm	20/30	20 %	0,65-C	0,85	0,35	0,90	1,05	0,85	0,55	0,50	0,65-C	0,85	0,55	1,00	0,90	0,85	0,60	0,55
	SX5	5 mm	140 mm	20/60	18 %	0,70-C	0,80	0,35	0,75	0,95	0,80	0,65	0,55	0,70-C	0,75	0,50	0,80	0,80	0,75	0,65	0,55
	SX8	8 mm	140 mm	20/60	29 %	0,80-B	0,85	0,30	0,75	1,00	0,90	0,75	0,70	0,85-B	0,85	0,50	0,80	0,90	0,85	0,80	0,70
	RS5	5 mm	40 mm	20/30	16 %	0,65-C	0,80	0,35	0,70	0,95	0,80	0,65	0,50	0,65-C	0,75	0,50	0,75	0,80	0,75	0,65	0,50
	RS8	8 mm	40 mm	40/30	13 %	0,60-C	0,70	0,35	0,70	0,85	0,70	0,55	0,45	0,60-C	0,65	0,45	0,70	0,70	0,65	0,55	0,45
	QS	20 mm	190 mm	40/140	28%	0,5-D	0,65	0,35	0,70	0,85	0,50	0,45	0,40	0,75-C	0,75	0,40	0,75	0,75	0,80	0,75	0,65
	RP8-C10	8 mm	∞	10/40	2,8%	0,65-C	0,70	0,40	0,75	0,80	0,65	0,60	0,60	0,75-C	0,75	0,40	0,75	0,80	0,80	0,70	0,65
	RP8-C20	8 mm	∞	20/40	1,7%	0,60-C	0,70	0,35	0,80	0,80	0,70	0,55	0,45	0,65-C	0,70	0,40	0,75	0,70	0,70	0,60	0,50
	RP8-Bar	8 mm	∞	Barcode	1,6%	0,50-D	0,60	0,40	0,70	0,70	0,60	0,45	0,35	0,55-D	0,60	0,40	0,70	0,65	0,60	0,50	0,40
	Linear	12 mm	∞	50	24%	0,70-C	0,80	0,30	0,90	1,00	0,75	0,60	0,65	0,70-C	0,80	0,50	0,95	0,85	0,75	0,60	0,65
	Linear	62 mm	∞	100	62%	-	-	-	-	-	-	-	-	0,95-A	1,00	0,35	0,95	1,00	1,00	0,95	0,75

* Tested with 200 mm airgap only, no insulation.

Figure 3: Nano microperforated panels (ceiling), QS slotted and inear wooden ribs absorption coefficients (Gustafs, 2019)

ACOUSTICS (sound absorption)	1000Hz	2000Hz
AUDIENCE AND SEATING		
Children, standing (per child) in m2 units	0.40	0.42
Adults per person seated	0.45	0.45
Adults per person standing	0.43	0.45

Table 4: Acoustic coefficients of audience and seating (Acoustic Traffic, 2019)