accon UK
ENVIRONMENTAL CONSULTANTS

BUILDING & ARCHITECTURAL ACOUSTIC DESIGN

NOISE • VIBRATION • EIA • AIR QUALITY • DAYLIGHT & SUNLIGHT • LIGHTING • ECOLOGY

ACCON UK Limited (ACCON) is one of the leading niche environmental consultancies, specializing in noise & acoustics, vibration, air quality, daylight & sunlight and Environmental Impact Assessments.

Building & Architectural Acoustic Design

If your project needs an acoustic consultant ACCON UK can help. We offer a range of consultancy services in architectural acoustics and the acoustic design of buildings. ACCON acoustic consultants have been involved in major building projects covering a wide range of uses through all RIBA design stages. Most buildings in the following sectors will require architectural acoustic design inputs:

- Residential - Approved Document E compliance
- Schools - Building Bulletin 93 (BB93) compliance
- Hospitals - in accordance with Health Technical Memorandum HTM 08-01
- Care homes
- Offices
- Hotels.

Although the exact regulatory requirements & sector guidance varies, architectural acoustics projects typically involve consideration of:

- The external ambient noise levels affecting the site
- Internal ambient noise levels which are controlled by the building envelope sound insulation and the ventilation systems
- Airborne and impact sound insulation and acoustic privacy between rooms
- The acoustic design of rooms for speech or other specific uses and acoustic treatments for circulation spaces
- Building services noise & vibration, including transmission within the building and effects on neighbouring premises.
- Groundbourne reradiated noise from underground rail systems & mining

ACCON can provide a complete acoustic design service for any scale of project.

To discuss your project please contact: Graham Parry (Managing Director)
on **0118 9710000** or via graham.parry@accon-uk.com
or visit our website www.accon-uk.com




Welcome to

Building Acoustics, brought to you by the Institute of Acoustics

The Institute of Acoustics is UK's professional body for those working in the disciplines of acoustics, noise, sound and vibration. This publication has been written for people whose job touches on areas of acoustics and who want to find out more.

Building Acoustics explores the importance of acoustics in the built environment, and how acoustics should be considered right at the beginning of a project. It also discusses the vitally important effect of noise on buildings users' health and wellbeing.

Well-designed buildings provide spaces that are comfortable, enjoyable and enable us to live effectively – they are an important aid to happiness.

There are elements of a building that are obvious to the effective use, such as doors or electrical power, but there are other elements that are equally as important in our experience of buildings but are not immediately obvious, and the acoustics of a building is often one such component.

However, there is often a considerable amount of effort that is invested by clever acousticians to enable a building to function properly and, in turn, provide comfort and enjoyment for the occupants. The building acoustics discipline mirrors the varied human interactivity in spaces and this publication aims to provide you with a snapshot of these considerations.

- Have you ever compared your experience of an old museum vs. a modern equivalent?
- How can we make our future living environments sound pleasant?
- Why is it sometimes difficult to hear someone talking to you and what has the built environment got to do with this?
- You probably know that tall buildings are designed to move – did you know they made sounds too?

Please read on to find out more!

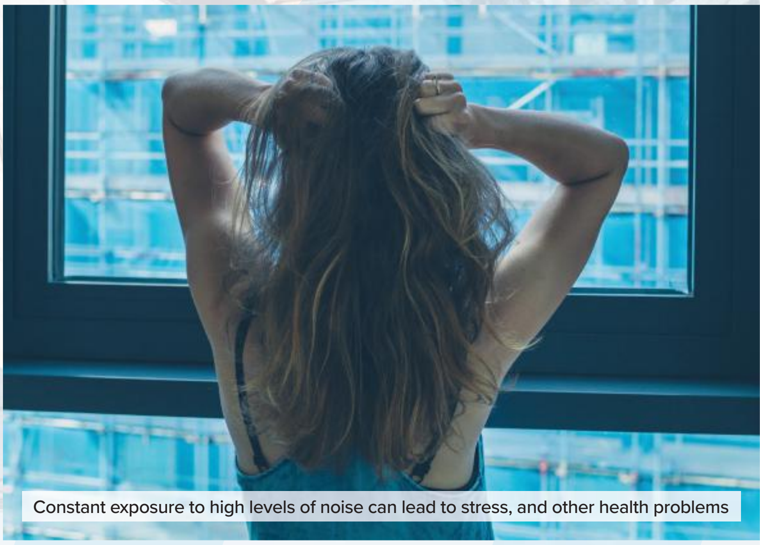
James Healey BSc (hons) MIOA APM PMQ
Chairman of the Institute of Acoustics Building Acoustics Group

The Institute of Acoustics is very grateful for the support of all the advertisers in this publication.

How can we make our future living environments sound pleasant?

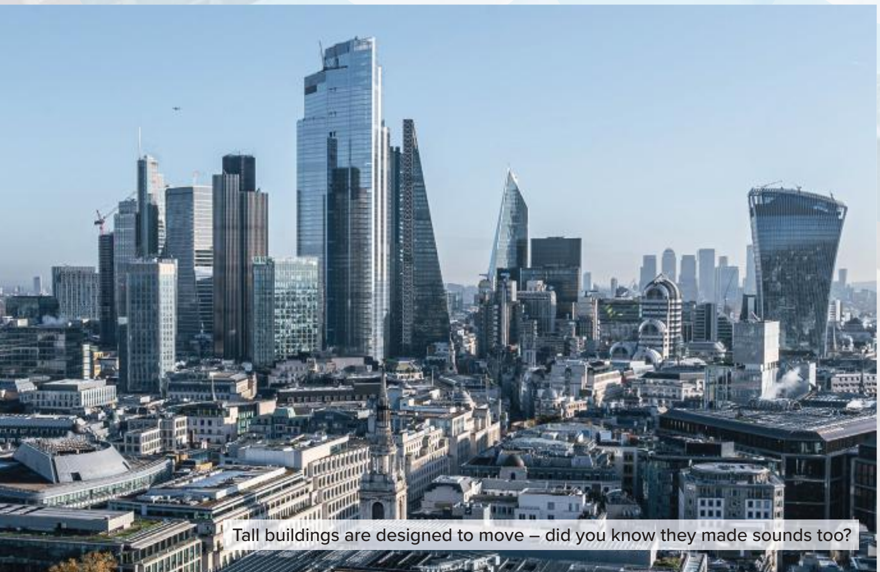

The work of acousticians and the acoustics industry has the power to design a better future

Have you ever compared your experience of an old museum vs. a modern equivalent?


Constant exposure to high levels of noise can lead to stress, and other health problems


Why is it sometimes difficult to hear someone talking to you and what has the built environment got to do with this?


Acoustic comfort is not a luxury, but rather a very important part of the pedagogy process


Tall buildings are designed to move – did you know they made sounds too?


Restoring Notre-Dame Cathedral through acoustic digital reconstructions

IOA BUILDING ACOUSTICS

Contacts

Publisher
Juliet Loiselle

Editor:
Nicky Rogers
Email: nickyr@warnersgroup.co.uk
Tel: 01778 391128

Advertising:
Dennis Baylis MIOA
Email: dennis.baylis@ioa.org.uk
Tel: 00 33 (0)5 62 70 99 25

Published and produced by:
The Institute of Acoustics
Silbury Court,
406 Silbury Boulevard,
Milton Keynes,
Buckinghamshire MK9 2AF
Tel: 0300 999 9675

Designed by:
Warners Group Publications
The Maltings, West Street
Bourne, Lincs
PE10 9PH

This publication is printed by Warners 01778 395111

The enhanced knowledge of human response to sound will allow the active curation of sound environments (soundscapes) specifically designed to improve comfort and wellbeing.

The Institute of Acoustics is the UK's professional body for those working in acoustics, noise and vibration. It was formed in 1974 from the amalgamation of the Acoustics Group of the Institute of Physics and the British Acoustical Society. The Institute of Acoustics is a nominated body of the Engineering Council, offering registration at Chartered and Incorporated Engineer levels.

The Institute has over 3,000 members working in a diverse range of research, educational, governmental and industrial organisations. This multidisciplinary culture provides a productive environment for cross-fertilisation of ideas and initiatives. The range of interests of members within the world of acoustics is equally wide, embracing such aspects as aerodynamics, architectural acoustics, building acoustics, electroacoustic, engineering dynamics, noise and vibration, hearing, speech, physical acoustics, underwater acoustics, together with a variety of environmental aspects. The Institute is a Registered Charity no. 267026

Institute of Acoustics
Sound • Noise • Vibration

Noisy neighbours upstairs?

There is strong evidence that some lightweight separating floors can generate high levels of low frequency noise, which could lead residents in flats to complain about footfall noise etc from their neighbours above, even when the floor meets the current ADE acoustic requirements.

By Seth Roberts, Principal Acoustic Consultant, Hayes McKenzie Partnership Ltd

Above: Research has confirmed links between reported levels of annoyance and constructions using timber (and composite) joist floors

This issue has led the Association of Noise Consultants (ANC) to recommend a large scale study into low frequency impact sounds linked to lightweight timber floor constructions.

Within the construction industry, sound insulation has gradually become a more important element of the building regulations since guidelines on this were first introduced into the 1965 building regulations (Part G). The building regulations 1992, introduced field testing of sound insulation for construction types that were not pre-approved constructions detailed within Approved Document E (ADE). When the 2003 building regulations came into effect, ADE included requirements for pre-completion testing of airborne and impact sound insulation for any construction not built to robust details by an approved contractor. (A robust detail (RD) is a separating wall or floor construction which has been assessed and approved by Robust Details Limited. In order to be approved, each robust detail (RD) must be capable of consistently exceeding the relevant regulatory performance standards and be practical to build on site).

Building a database of test results for different construction types

In July 2003, the ANC set up a registration scheme for pre-completion testing allowing members of the scheme to carry out testing for demonstrating compliance with the building regulations. The ANC registration scheme also served the purpose of building a database of test results for different construction types which could be used for research purposes. 20 years down the line, a great deal more is known about sound insulation and potential problems with certain construction types.

One such problem that has emerged over the last 20 years of pre-completion testing, is the fact that the required performance standards for impact sound transmission set out within ADE may not be sufficient to adequately protect future occupants against intrusive levels of noise from vertically adjacent flats. The problem is linked with certain construction types which, although they meet the requirements of ADE, appear to lead to complaints from occupants about impact sound from normal footfall being very intrusive or even intolerable. This problem has been widely reported across the acoustics industry and has led to further research into acceptable levels of impact sound transmission. P08

“The required performance standards for impact sound transmission set out within ADE may not be sufficient to adequately protect future occupants against intrusive levels of noise from vertically adjacent flats”

Occupant dissatisfaction.

In 2015, Jack Harvie-Clark of Apex Acoustics gave a presentation at the Institute of Acoustics conference in Harrogate. The presentation covered international impact sound transmission standards and research into low frequency impact sound that can occur between flats built around a timber frame construction. The research confirmed links between reported levels of annoyance and constructions using timber (and composite) joist floors. The main issue that was highlighted is the fact that the UK building regulations, and specifically the performance standards for impact sound transmission contained within ADE, do not cover the low frequencies which are driving complaints for these construction types. The requirements of ADE specify maximum levels of impact sound within a frequency range of 100-3150 Hz, but impact sound transmission in frequencies below this range have been found to strongly correlate with occupant dissatisfaction.

In 2016, the ANC Good Practice Committee setup a working group to investigate suitable methods for controlling the identified problem of low frequency impact sound linked with timber frame constructions. The main aim of the working group was to establish an appropriate way of identifying the problem during pre-completion testing. In June 2023, the working group provided recommendations on two possible methods for identifying and assessing low frequency impact sound transmission linked with timber frame constructions. P10

Assessment methods

The first (and preferred method) is based around use of the exiting $L_{nT,w}$ parameter (weighted standardised impact sound pressure level) which is already specified within ADE but including an additional 'spectrum adaptation term' (C_I) which provides a correction to the result based on characteristics within a frequency range of 20-2500 Hz. The method for inclusion of a spectrum adaptation term such as this is something which is already set out within Annex A of BS EN ISO 717-2[1] but the standard only recommends a frequency range of 50-2500 Hz and does not extend as low as 20 Hz.

The ANC working group proposes the use of a spectrum adaptation term that has been developed as part of a series of Swedish research projects (the AkuLite project; the Aku20 project and, most recently, the Akutimber project). All three of these research projects build on the initial findings that a strong correlation existed between perceived annoyance and inclusion of a spectrum adaptation term covering the extended frequency range 20-2500 Hz. As part of the Akulite Project, an alternative spectrum adaptation term using a more complex frequency weighting than that set out in ISO 717-2 and covering a frequency range of 20-2500 Hz was proposed ($C_{I,Akulite}$). It is the combination of the weighted standardised impact sound pressure level and the adaptation term: $L'_{nT,w} + C_{I,Akulite}$ (known as the Akulite index) which is proposed by the working group as the best method for assessing low frequency impact sound transmission.

The working group acknowledge that the first method would require instrumentation to be adapted to measure and assess the appropriate frequencies and that it may therefore be helpful to consider an alternative method that could easily be used by consultants already working in this field. The alternative method proposed by the working group includes the use of both $L'_{nT,w}$ and the spectrum adaptation term $C_{I,50\text{-}2500}$ as defined in ISO 717-2. The recommendation is that $L'_{nT,w} + C_{I,50\text{-}2500}$ should be no more than 4 dB higher than the $L'_{nT,w}$ requirement in line with the Class A and Class B standards set out in ISO 19488[2] .

Ongoing research

Whilst making these recommendations for methods of quantifying and assessing low frequency impact sound transmission, the working group acknowledges that more research is required in order to fully understand the mechanisms and resultant perceived effects. The working group is therefore also recommending that laboratory test data on impact sound transmission down to 20Hz is gathered through a large scale study of different lightweight construction types. The results of such a study would be used to inform designers, architects and builders on suitable constructions to avoid significant levels of low frequency impact sound transmission. The goal of the ANC working group is to propose a repeatable and reproducible test and assessment method for inclusion in the next revision of ADE along with guidance on construction methods that could be incorporated into robust details. ◎

Watch the ANC video about why sound testing is so important:
https://www.youtube.com/watch?v=roFKUmNJJMY

Footnotes

1. BS EN ISO717-2 Acoustics — Rating of sound insulation in buildings and of building elements — Part 2: Impact sound insulation, BSI, 1997
2. ISO TS 19488 Acoustics — Acoustic classification of dwellings, ISO, 2021

Below: Architects' visualisation of the development

Soundscape design for a residential development: a case study

A co-housing development, Co-HUT (Co-Housing upon Tyne), has been proposed in Newcastle upon Tyne, comprising 25 dwellings and communal spaces arranged in blocks around a courtyard. Apex Acoustics Ltd initially did a traditional noise impact assessment for the site in support of a planning application and later adopted a soundscape approach to see where improvements could be made as the stakeholders of the development are also its future residents.

By Seena Sajeev, Rebecca Romeo Pitone, Danuta Nabiałek, Julien Batten and Jack Harvie-Clark, Apex Acoustics Ltd

The site is close to the River Tyne, with Scotswood Road to the south and Atkinson Road to the west. Noise from industrial sites to the south, east, and west are less prominent in comparison to the road traffic noise. Site location and layout shown in Figures 1 and 2. Architect's visualisation is shown on previous page.

Above:
Figure 1: Site location

Above:
Figure 2: In-situ soundwalk locations, with the proposed building showing as white blocks

Data collection and analysis

The idea for a soundscape assessment was initially presented to the residents in a focus group session, where their concerns and aspirations about the sound environment of their future homes were also discussed. Further data collection followed ISO 12913-2[1] and was carried out in two parts:

1. in-situ; and
2. virtual soundwalks.

The in-situ soundwalks were carried out with the residents and covered weekday daytime, late evening and weekend periods. Binaural measurements (a method to record sound in the same way that we hear it – with two ears, which gives us a sense of where sounds are located create a 3-D spatial sound sensation) with point-of-view video were made during the in-situ soundwalks and other appropriate times, which were processed to create auralisations and visualisations[2] for the virtual soundwalks. These were conducted over Zoom with the future residents.

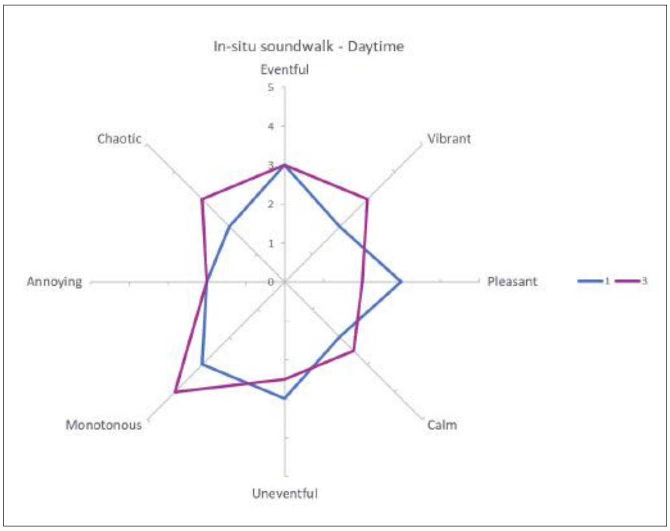
The in-situ soundwalks covered four locations on the site with varied soundscape and proposed uses. The soundwalk locations are shown in Figure 2, (locations 1 and 3 represent residential blocks, while 2 and 4 represent garden areas of the development.)

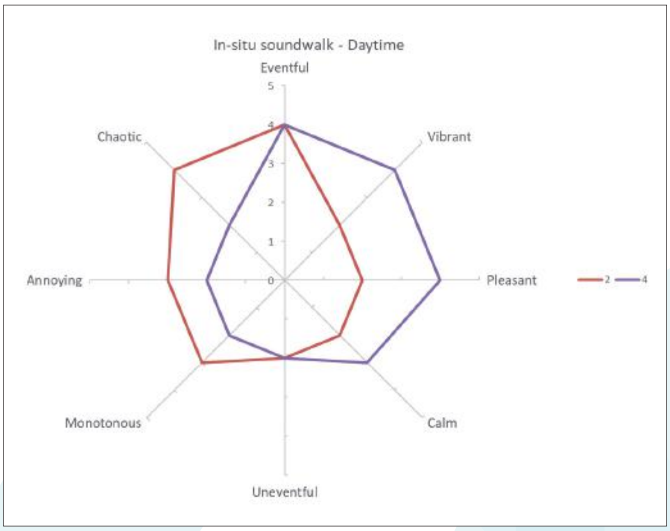
The virtual soundwalk with the residents covered indoor sound environment scenarios at locations 1 and 3 with windows partially open and closed, and the courtyard sound environment. The virtual soundwalk with members of the public included the same indoor scenarios and outdoor scenarios for locations 1 and 3, with the exception of the courtyard scenario, which was included on the residents' request. A 16 dB broadband attenuation (reduction) was applied for the partially open window scenarios, while the closed window scenarios were calculated based on the proposed glazing performance in the traditional noise assessment report. Sound was mastered in all auralisations and room reverberation added to all internal scenarios. The mastering involved dynamically limiting and normalising overall levels to maximise the dynamic range available across all scenarios. The virtual sound environment for the courtyard was based on the auralisation of the external sound environment at location 3, but with a 10 dB broadband attenuation, as indicated by the noise model. As the virtual scenes were presented online through Zoom (this work was carried out through the Covid lockdown), no calibration of each listener's experience was possible.

Questionnaires were used to record responses from the participants of the soundwalks for the outdoor scenarios and the indoor sound environment, and both questionnaires included sections where the participants could record their responses as scale values, and additional sections to record comments. P14

Footnotes

1. ISO/TS 12913-2:2018(en), 'Acoustics — Soundscape — Part 2: Data collection and reporting requirements', 2018
2. J Harvie-Clark, R Romeo Pitone, 'Acoustic Perception EvALuation in Buildings - The APEAL Method', Proc. Institute of Acoustics, vol 42, pt 1, 2020





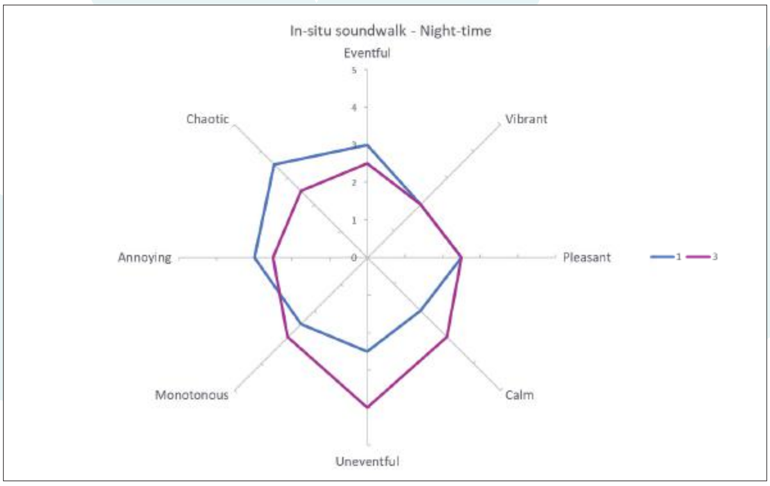
Above left: Figure 3: Median values of response to perceived affective quality – in-situ soundwalk during daytime at the locations of residential block elevations

Above right: Figure 5: Median values of response to perceived affective quality – in-situ soundwalk during daytime at the locations of external amenity areas

Responses to soundwalks

The measured daytime noise levels at locations 1 and 3 were different, however the soundscape assessment as shown in Figure 3 indicates quite similar responses to perceived affective quality. In complete contrast, although the measured night-time noise levels at locations 1 and 3 were similar, the soundscape assessment results are significantly different, as shown in Figure 4. This may be because of the type and traffic pattern of the surrounding roads; Scotswood Road to the south of the site is a dual carriageway with a steady traffic flow and is about 90m from the site. Traffic on Atkinson Road to the west of the site often labours up the steep hill and briefly stops for a mini roundabout to the immediate north-west of the site before setting off again. The measured average noise levels due to this road differs by 10 dB between daytime and night-time periods. The proximity of the road makes the intermittent traffic feel more intrusive, especially during the night when the background sound levels are lower.

The median responses to the perceived affective quality of the external amenity areas were also significantly different, as shown in Figure 5. This may again be because of the surrounding road traffic pattern.



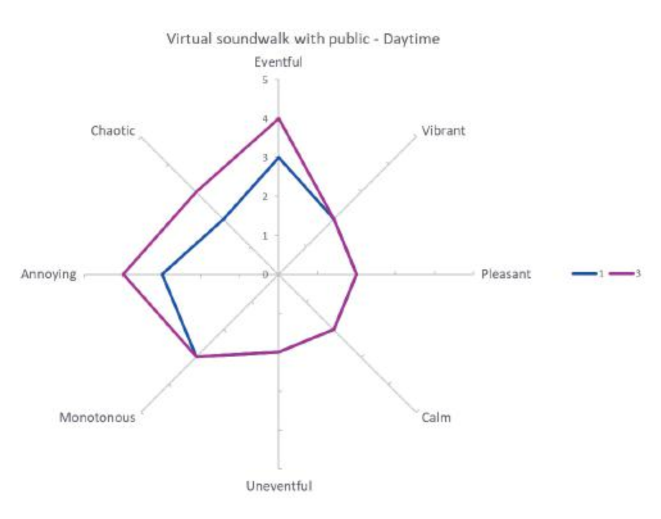
Above: Figure 4: Median values of response to perceived affective quality – in-situ soundwalk during night-time at the locations of residential block elevations

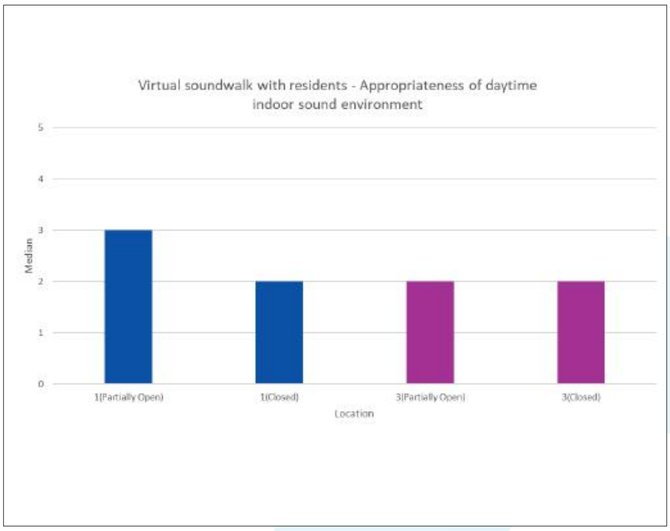
The external amenity area at location 2 is situated in line with Atkinson Road coming down the hill. To the listener, the sound of cars approaches directly, to become close and fast. These sounds are described as 'looming' sounds, which according Marsh[3] are perceived as particularly alarming as sounds which are loud and approaching directly, fast, represent the greatest danger and threat to life. Distant or receding sounds represent less danger, which is the case for the sounds at location 4.

Positive responses to the soundscape at location 4 is understood to be due to the presence of more natural sounds, especially birdsong, which was indicated in the comments and during the informal discussions as contributing to a positive sound environment. This is consistent with pieces of research[4 5 6 7 8], which indicate that the presence of natural sounds in combination with road traffic and industrial noise, or in the background, generally tend to reduce the perceived annoyance to a sound environment. In a study of outdoor urban soundscapes[9], sound environments dominated by natural sounds were perceived as 'pleasant', which agrees with the median responses to the perceived affective quality at location 4. The soundscape approach therefore revealed aspects of the sound environment at the site which were not apparent from the traditional noise assessment considering only the average decibel levels, and not the content or characteristics of the sound environment.

Footnotes

3. J. Marsh, 'There's a Bad Noise on the Rise: Looming Sounds Produce Behavioural Attentional Capture', ICBEN, 2021
4. S. Torresin, R. Albatici, F. Aletta, F. Babich, and J. Kang, 'Assessment Methods and Factors Determining Positive Indoor Soundscapes in Residential Buildings: A Systematic Review', Sustainability, vol. 11, p. 5290, Sep. 2019
5. W. Davies, N. Bruce, and J. Murphy, 'Soundscape Reproduction and Synthesis', Acta Acust. United Acust., vol. 100, Mar. 2014
6. M. Romanowska, 'The Warsaw soundscape - Structure and specifics', Misc. Geogr., vol. 18, Dec. 2014
7. C.-J. Yu and J. Kang, 'Soundscape in the sustainable living environment: A cross-cultural comparison between the UK and Taiwan', Sci. Total Environ., vol. 482–483, pp. 501–509, Jun. 2014
8. A. Gidlöf-Gunnarsson, E. Öhrström, M. Ögren, and T. Jerson, 'Good sound environment in green areas modify road-traffic noise annoyance at home', pp. 1579–1587, 2009
9. Ö. Axelsson, M. Nilsson, and B. Berglund, 'A principal components model of soundscape perception', J. Acoust. Soc. Am., vol. 128, pp. 2836–46, Nov. 2010





Above left: Figure 6: Median values of response to perceived affective quality – virtual soundwalk with members of the public, daytime scenario at the locations of residential block elevations

Above right: Figure 7: Median values of response to appropriateness of indoor sound environment – virtual soundwalk with residents

Responses and comments recorded by participants for different soundscape scenarios had notable differences; where a sound environment was considered appropriate by one person, it was also considered intolerable by another. Informal discussions revealed that non-acoustic personal factors such as the different sound environments of their current homes, and previous experience of living in proximity to road traffic noise of different extents, was a strong factor in the wide range of responses and comments.

In comparison to the in-situ soundwalk, the average responses to the perceived affective quality at location 1 and 3 were more negative for the virtual soundwalk with members of the public, as shown in Figure 6. This might be indicative of the limitations of the virtualisation techniques in providing an accurate re-creation of the in-situ sound environment. Placing the participants in a survey context could also have affected the responses.

The indoor sound environments were considered 'slightly' appropriate by the residents for the closed window scenario at location 1 and partially open and closed window scenarios at location 3, as shown in Figure 7. The partially open window scenario at location 1 was considered 'moderately' appropriate. The reason for the closed window scenarios receiving a lower or similar scale value in comparison to the partially open window scenario was understood from the participant comments to be because birdsong had been cut out; they preferred open windows with more birdsong, even if it meant more traffic noise. The absence of typical indoor residential sounds such as televisions, kitchen appliances, and conversations in the virtualisations of the indoor sound environments also meant the participants were listening keenly to outdoor sounds, which does not necessarily portray real life situations.

Facilitating co-creation and inclusivity

The soundwalk experience helped the residents recognise design improvements for the sound environment of their future homes. One of these included improved enclosing of the courtyard area to provide additional protection from intrusive road traffic noise, especially reducing the opening in the north-west corner. The inclusion of a courtyard was a positive design measure, which although not specifically intended for the purpose, provides all residents with a quieter façade. However, reducing the courtyard openings to help block out road traffic noise could not have been anticipated without the soundscape assessment.

Almost all the prospective residents considered birdsong as a positive element of the soundscape, and so in the discussion following the virtual soundwalk they suggested planting in the courtyard to attract more birds and thereby enhance natural sounds. The soundscape assessment revealed the external amenity area at location 4 as distinctly positive in comparison to location 2. It was therefore suggested by the residents to use location 2 for louder activities, e.g., children's play area, and use location 4 as an area for quiet and peaceful relaxation. These design responses could only be realised due to the soundscape assessment.

The soundscape approach therefore facilitated co-creation and inclusivity where the residents could contribute towards improvements to the sound environment of their future homes.

Conclusions

The soundscape assessment revealed aspects of the sound environment which were not evident from a traditional noise impact assessment and helped facilitate co-creation and inclusivity where the future residents of the development identified design improvements for the sound environment of their future homes. As an evolving and emerging field, soundscape exhibits great potential to improve sound environments, and thereby health and quality of life.

Accolades

Winner of Housing Design Awards 2022

John Connell Soundscape Award 2021

Association of Noise Consultants (ANC) Environmental Noise highly commended award 2021

A paper on the research was presented at Internoise 2022 at Glasgow.

Take the virtual soundwalk

See what you think about the noise around the Co-HUT development here

https://www.apexacoustics.co.uk/take-our-virtual-soundwalk/

A better built environment

The real-world performance of buildings is under scrutiny. But the part that the technical discipline of acoustics plays in supporting both people-centric and planet-conscious design outcomes is not always fully appreciated, yet we know that the role of acoustics impacts on multiple levels.

By Dr Andrew Bullmore, Director, Hoare Lea

Above:
The active curation of soundscapes can positively impact on human health, wellbeing and social cohesion *(Image courtesy of John Storock)*

Our buildings need to support improved human outcomes and there is not one decision-maker or leader on this planet who isn't at the mercy of human emotions, problems and desires.

Good acoustic design is key to bringing buildings to life for people. This imperative is coming into increasingly sharp focus, most recently through the immediate need for resilience against COVID, the need to futureproof against the extremes of climate change and the flexibility to accommodate ever-changing user expectations. It may not be immediately obvious, but all these factors have acoustic implications.

Sitting alongside the focus on human-centred design is the need to be guided by doing right by our planet. The situation demands change so we can either be part of this change, or we can watch it happen without us. The climate emergency has focused minds on the need to reduce the carbon associated with buildings (embodied or operational). If essential climate emergency trajectories are to be met buildings will need to be constructed and operated with operational energy use approximately 60% smaller than has traditionally been the case, with material circularity (reduce-reuse-recycle-recover) also becoming increasingly relevant. Again, the delivery of successful acoustic outcomes has implications on achieving targets for both embodied and operational carbon, and circularity.

The work of acousticians and the acoustics industry has the power to design a better future. Crucially, acousticians understand that human-centred design solutions aren't always the best choice for the planet and, conversely, achieving net zero carbon and other planet-conscious objectives can result in negative outcomes for building users. Balancing this tension is where the industry problem-solving culture shines.

Sound falls into two distinct categories: physical sound and perceived sound. Ultimately it is the perception of sound that matters in delivering a better built environment in terms of human outcomes. It is therefore right we should start with perceived sound as our primary driver in designing buildings that we can declare to be 'acoustically high performing'. However, to deliver such human outcomes with confidence, while simultaneously delivering better outcomes for the planet, requires an intimate appreciation of the underlying science.

Human health and wellbeing

The clear starting point for considering the acoustics of a high performance building lies in the comfort and wellbeing of its users. Somewhat counterintuitively, and excepting buildings such as auditoria or recording studios for which acoustics is their prime function, is where good acoustic design should be 'silent'. Building users should be immersed in an environment that is subconsciously conducive to them feeling and delivering at their very best. Whatever the building's prime function may be, it should be taken as read that the very highest performing buildings should provide an optimally designed acoustic environment as standard.

Human outcomes are considered at two levels. Firstly, the direct impact of indoor environmental quality on human health and wellbeing. In this regard sound is one of the key indoor environmental factors needing to be considered (not forgetting that vibration also falls within the technical discipline of acoustics). Poorly controlled acoustic environments can lead to disturbance, annoyance and stress leading to raised blood pressure even at relatively low amplitudes, while prolonged exposure to higher levels of sound can cause irreversible damage to hearing.

The second human outcome is the degree to which the acoustic environment promotes productive output. In this context 'productivity' may be defined quite differently for any given space or building typology. As a rudimentary example, the prime function of a bedroom is to enhance sleep, whereas promoting sleep in a teaching environment would be the least desirable outcome.

Fundamental acoustic design considerations which acoustic designers take for granted as leading to improved human outcomes include the control of:

- sound levels in rooms, either from noise sources within the building itself such as ventilation systems or the intrusion of external noise (e.g. typically from transportation sources);
- reverberant sound build-up within rooms;
- sound transmission between adjacent internal spaces; and
- sound egress through the building façade.

However, there are some sectors and building types where acoustics should no longer remain a 'silent' discipline to good design, but instead should 'shout' the presence of the highest quality acoustic design to become front and centre of the building users' experience. For such developments it is essential that the aspirations and needs of the user are fully explored and understood. Obvious examples are buildings where the reproduction of sound is their prime function (concert halls, auditoria, sound and film recording studios, etc). There exists, however, a multitude of less obvious building typologies where acoustic design is fundamental to the building functionality. In the science and research sector there is increasing demand for facilities benefitting from ultra-low noise and vibration environments required for undertaking sub-atomic scale measurements. At the other extreme, the space industry is developing new facilities for the testing of propulsion systems and their payloads, both of which involve the generation and control of ultra-high levels of noise and vibration.

Regardless of the extremes concerned, these are all design tasks whose successful delivery demands an understanding of the fundamental physics of acoustics behind the design principles required to drive real-world outcomes. These outcomes also increasingly demand that acoustics be considered in tandem with other technical disciplines to ensure that truly holistic outcomes are delivered.

Our scientific understanding of the pathways to human perception of sound is evolving; traditionally, acoustic specifications have been based around the concept of sound amplitude, often expressed as a single numerical decibel limit. These limits have largely been derived from social surveys which have sought to aggregate the typical subjective response at a community level from the self-reported response of populations. However, it has long been acknowledged that the response to the same sound stimulus can vary widely between individuals. Large variations in response can occur even for the same person when exposed to the same sound stimulus but across different contextual settings. A combination of advances in non-invasive neuroscience coupled with the analytics of large data sets using machine learning techniques is beginning to provide much greater insight into the complexities of human sound perception.

Soundscapes

The emerging field of 'soundscapes' is introducing the derivation of entirely new objective for describing sound environments, with some of these metrics beginning to account for context, including interactions between the senses and especially visual cues. Perhaps most significantly for the delivery of future high performance buildings, this enhanced knowledge of human response to sound will allow the active curation of sound environments (soundscapes) specifically designed to improve comfort and wellbeing. In so doing the traditional reliance on designing according to sound levels, with assumed level-driven boundaries between what is considered to be an acceptable versus an unacceptable level of sound, will become a contextualised spectrum of impacts to be more finely managed. P18

Planet-conscious design

With sound and vibration both acting as physical triggers for evoking human senses, it's easy to appreciate how good acoustic design would naturally lead to improved human outcomes. Perhaps not so immediately apparent, is the part played by acoustic design in helping to deliver high performance buildings which directly addresses the need for planet-conscious outcomes. That said, acoustic design has its own part to play in this respect.

As far as high performance buildings are concerned, planet-conscious design can broadly be classified into three main areas:

- energy and carbon;
- material resource; and
- biodiversity.

Controlling both sound and vibration to within acceptable levels in the built environment generally requires some form of physical intervention, invariably leading to material resource usage and therefore the potential for associated embodied carbon. Some physical interventions are also associated with the potential to be directly responsible for operational carbon.

Interventions

One common example of an intervention with both embodied and operational carbon is the inclusion of 'in-duct acoustic attenuators'. These are commonly used to reduce fan noise generated by air movement systems to acceptable levels within occupied spaces. However, one consequence of an acoustic attenuator's ability to reduce sound energy is the introduction of additional resistance to air movement which, if not carefully considered in the mechanical design, may increase the electrical energy required by the fan(s). Depending on the electrical carbon intensity at the time, increased energy consumption equates directly to increased carbon emissions. Consideratrion of the energy used to manufacture, deliver and install each attenuator, plus the embodied carbon in the materials is therefore important.

Another common example of a physical intervention includes the excessive specification of materials in partition, floor and façade components to enhance their resistance to the transmission of sound and vibration. This results in the manufacture, delivery, and installation of additional construction materials, plus the inextricable embodied carbon.

An acoustically high performing building is one which strikes the appropriate balance between delivering the acoustic performance required for positive human outcomes while being mindful of the resultant environmental impacts from the design interventions required to achieve those outcomes. This need for balance may lead to an interesting shift in the approach to acoustic performance specification. To further elaborate, established research informs that a difference of 3 dB(A) is subjectively the smallest perceptible change in sound level under practical, real-world conditions.

Which leads to the question what environmental benefits could potentially be achieved by way of a relaxation in target sound criteria up to 3 dB(A), thereby reducing the quantum of sound and vibration control interventions. Whike at first, individual gains may only be small, but cumulative benefits could become significant in the global context.

Added to this is the prospect that compliance-led acoustic design, based solely on the specification of target dB criteria, may be moving into a new era. This step change will emerge from the previously mentioned research into a soundscape-based approach, thereby furthering our understanding of the subtleties of human responses to the characteristics and context of the sound environments to which they are exposed.

Building technologies

The foregoing examples assume a 'business as usual' approach to delivering beneficial acoustic outcomes. However, the world we live in today is anything but 'usual'. Rapid advances are occurring across a whole range of building technologies, including digital enablement, materials, manufacturing and approaches to both off-site and on-site construction. Research is simultaneously leading to advances in our underlying scientific understanding of both physical acoustics (in particular, the acoustic properties of materials) and human response to sound, while technology is enabling ever more sophisticated numerical modelling to be performed. Surely, now is the time to take a step back from the norm and take a more holistic, outcomes-focused, approach to delivering truly sustainable buildings.

Building construction hasn't fundamentally changed for decades. Buildings still rely primarily on the delivery of materials to site where construction workers craft a basic shell, with multiple trades subsequently attending site to fit out and modify that shell to deliver the building to its required, typically compliance driven, specification. However, the emergence of design tools integrated with factory-based modern methods of construction (MMC) means this traditional approach no longer needs to remain the status quo. Under this transformation, the

Left:
Windows need to variously connect occupants with, and isolate them from, the building's external environment

more radical the thinking, and the greater the emphasis placed on achieving truly holistic outcomes across both human-centric and planet-conscious spheres of influence, the better.

Window design

Using the window as an example of how taking a more outcomes focused, systems-thinking approach to design, and making use of modern technologies, could provide far reaching benefits, we need to start with the most fundamental question: what basic functions does a window serve?

Windows provide a connection between a building's occupants and the outside world. Whether open or closed, clear glass allows daylight and warmth in and views out. When open, windows provide an even greater connection by providing a conduit into buildings for fresh air for ventilation, thermal comfort and for the sounds of nature. It is hard to argue that any of these attributes can deliver anything other than beneficial human outcomes.

However, such a connection with the external environment isn't always desirable. At night, for example, we often wish to exclude artificial light from road traffic or streetlights, as well as prevent views from outside to in. We address these issues by adding opaque coverings to windows in the form of internal curtains or blinds, and shutters (internal or external). During the day, solar gain through windows may also result in overheating which is commonly addressed using blinds, curtains, shutters, or external solar shading.

Also, if the act of opening a window doesn't allow ingress of fresh air or the sounds of nature, but instead results in poor external environmental conditions associated with low air quality and excessive noise due to road traffic? The 'solution' in such cases is to keep windows closed, or to provide permanently sealed windows which facilitates the exclusion of poor external environmental conditions. But this action introduces the need to provide a means of ventilating the internal space, requiring the introduction of some form of forced system. Whether such systems are local or central they come with attendant energy requirements, potentially leading to improved human-centric outcomes at the cost of poorer planet-conscious outcomes. Where some form of mechanical cooling is required, this will also introduce attendant energy requirements, resulting in increasingly critical challenges. This is due to the increased occurrence of climate change-induced temperature extremes and the need to provide better insulated buildings to accommodate new thermal technologies such as heat pumps.

User control

The complex balance between human-centric and planet-conscious outcomes is further complicated by the traditionally perceived benefit of affording building users some degree of control over their internal environment, including their ability to open and close windows and/or the associated window coverings. This must now be considered in the context of the energy and emissions associated with such control, including impacts on the effectiveness of the ever increasing complexity of ventilation, cooling and heating strategies.

Based on the above, even the humble window has a host of (often competing) outcomes to deliver on behalf of building occupants. Not least, windows need to P20

variously connect occupants with, and isolate them from, the building's external environment.

Specific considerations have thus far included: daylight; views; light pollution; visual privacy; sound; ventilation; air quality; heating; and cooling. Other design considerations include security, fire safety and façade access/building maintenance, etc.

The question the acoustics community is asking itself is whether the design of the high-performance building of the future could benefit from acoustic designers taking a step back to look at the issues from a systems perspective in tandem with engineers and designers from other technical disciplines.

When adopting a systems-thinking approach the window should be considered an integral part of a system, which includes the whole of the building's façade, as well as the building's ventilation, thermal management systems, control strategies and its occupants.

Modern methods of construction

Recent advances in MMC, including the multiple benefits afforded by off-site factory production environments, opens the possibility of better integrating multiple outcomes within the design and construction of the building structure itself. Focusing on acoustics, complete façade elements (including windows) could be delivered to site with a warrantied composite sound insulation performance. These façade elements could include integral features such as controllable ventilation paths with built-in acoustic attenuation to control the passage of sound. Current developments in acoustic metamaterials could revolutionise the form of acoustic attenuation, as could future developments in active noise control. Integral ventilation paths would no longer have to rely on the windows and could also include integral air movement devices, comprising energy harvesting elements all integrated into the façade. These façade-integrated ventilation paths could equally host thermal transfer and air filtration components. All of which possible by the façade manufactured under closely controlled factory conditions, as opposed to constructed under uncontrollable on-site conditions. The environmental benefits associated with reductions in energy, embodied carbon and waste in both manufacture and construction, plus greater material traceability and circularity, would be significant. Equally significant would be the guarantee of precision manufactured units delivering both better installed performance in all regards, (including acoustics) and human-centric outcomes.

Building intelligence

Also worthy of consideration as part of any new approach to the design and operation of high performing buildings is the impact that advances in building intelligence (often referred to as smart building technologies) may have. A prudent and targeted deployment of these technologies could simultaneously yield both better human-centric and planet-conscious outcomes.

Again, this concept may be illustrated by reference to providing adequate ventilation and cooling to internal spaces (often via opening windows) while simultaneously protecting against external noise ingress. Under many practically encountered situations, external noise levels are not constant but instead exhibit significant diurnal variations. This is particularly the case with road traffic, which is a primary source affecting buildings. Likewise, acceptable levels of noise in internal spaces may also vary depending on the time of day or night. However, as previously mentioned, the common 'solution' to protecting building occupants against external noise is to include non-openable windows in noise-exposed façades. The problem with this is that it removes the option for building occupants to choose natural ventilation via open windows even at those times when the external noise levels are acceptably low. It also removes the option to remove excess heat by passive cooling particularly when noise ingress cannot negatively affect absent occupants.

Monitoring

A more targeted approach to maintaining the appropriate balance between human-centric and planet-conscious outcomes could be based around evidence provided by sensed data. The real-time monitoring of internal versus external environmental conditions could provide essential information to building users, allowing them to self-evaluate the benefits/disbenefits of taking certain actions. For example; the simultaneous monitoring of external and internal noise levels, temperature and air quality could all provide information to inform occupants on the appropriate course of action. The same information could equally be fed into enhanced Building Management Systems (BMS) to toggle noise attenuation components integrated within passive or mechanical ventilation systems. To better engage building users, evidence could simultaneously be provided as to the anticipated benefits resulting from any such automated control, both from an indoor environmental quality and an energy saving perspective.

There also exists the possible sensing of occupancy patterns simultaneous with the monitoring of internal environmental quality, including the acoustic environment, to gather real-world evidence on the degree to which sound contributes to occupants' preferred choice of locations. Such information could usefully inform future acoustic design criteria on the basis of behavioural as opposed to questionnaire-based evidence.

Building performance

No single building can be considered in isolation, but rather, each exists as part of a wider built environment ecosystem.

Even within the boundaries of the building itself, there exists the complex ecosystem comprising the interaction between a building and its occupants. These two components cannot be considered in isolation; the performance of a building impacts on the performance of people, just as the behaviour of people impacts on the performance of the building. This bidirectional interaction has effectively been recognised in the previous discussion regarding the need to manage the tensions between delivering human-centric and planet-conscious outcomes.

However, when determining what is required to deliver a truly high performing building, consideration needs to extend far beyond the physical boundaries of the building itself, because those physical boundaries are permeable.

Creating 'good' sound environments

As people flow through buildings, they interact with the spaces between buildings. It is vital that the environments in these spaces encourage walking, cycling and socialising and create meaningful dialogue between individual buildings and the wider built environment. The curation of spaces between buildings in this manner is known to be crucial in creating healthy, vibrant spaces that promote wellbeing and wider social benefits. Beyond these spaces, people also interact with the transportation networks that facilitate wider access to the built environment. Acoustics has its own part to play in this general arena. Previously mentioned advances in soundscape research are increasing the understanding of what characteristics constitute 'good' sound environments. This understanding will increasingly inform how soundscapes should be proactively designed and managed. However, that is looking more towards the future. In the immediate term acousticians have long played a vital role in managing the transmission of noise across a building's boundaries. This includes both the control of external noise ingress into the building and the control of noise radiation from the building to prevent adverse impacts on the neighbouring environment including other buildings.

Secondly, high performance building design needs to properly account for the movement of resource and materials across buildings' boundaries. This includes incoming resources in the form of utilities and associated bi-products comprising 'products' and waste. In this context, the word 'product' is used to define the primary intended output function of the building, be this a physical product in the traditional sense of the word, or educated pupils from an academic establishment, or recovered patients from a healthcare establishment etc.

Carbon, social and environmental impacts

The delivery of a truly high performing building cannot ignore these multiple connections with the wider world. This is particularly the case with the onset of net zero carbon and environmental, social and governance strategies. These increasingly demand evidence of carbon, social and environmental impacts along the complete supply chain, which is whe acousticians can not only bring their extensive experience in building design to bear, but can usefully call on their wider expertise in the acoustics of energy generation and transmission, transportation systems (including road, rail and air) and also the impacts of noise on wildlife, a factor which is becoming increasingly important in managing biodiversity. ◎

This article should remind you that:

- The climate emergency has focused minds on the need to reduce the carbon associated with buildings (embodied or operational).
- Recent advances in modern methods of construction opens the possibility of better integrating multiple outcomes within the design and construction of the fundamental building structure itself.
- The criticality of curating spaces between buildings is universally recognised in creating healthy, vibrant spaces that promote wellbeing and wider social benefits.

IOA education and training in building acoustics

The Institute of Acoustics (IOA) offers a range of professionally recognised training for those interested in careers involving building acoustics and those already practising in the field who wish to brush up on basic concepts, methods, standards, guidance and legislation.

By Professor Keith Attenborough, IOA Education Manager

Certificate of Competence in Building Acoustics Measurement (CCBAM)
The main aim of this five-day course is to train delegates to carry out and report upon sound insulation tests on walls and floors in accordance with relevant standards and regulatory instruments. Its main focus is on the measurement requirements of BS EN ISO 140 parts 4 and 7 and BS EN ISO 717 parts 1 and 2, but it is useful in respect of other requirements including those in Building Regulations (Annex B of Approved Document E in England, Booklet G in Northern Ireland, Technical Handbook 2010 Section 5 in Scotland) and those relating to schools, hospitals (Health Technical Memorandum 08-01) and offices.

There is an examination on the final day and the course assessment includes a practical test. Usually, exams take place in April and November.

More details and up-to-date information about accredited Training Centres and dates are here: **https://www.ioa.org.uk/training/certificate-competence-building-acoustics-measurement**

Certificate of Competence in Irish Building Acoustics Measurement (CCIBAM)
An update to the Irish Building Regulations, which came into force for all new projects starting on site on or after 1 July 2015, requires mandatory pre-completion acoustic testing by competent individuals and the CCIBAM course addresses this requirement.

The course content duplicates much of that of CCBAM but will cover primary differences between UK and Irish requirements relating to:

- schools and healthcare buildings;
- building regulation tests;
- access to Quality Management Schemes; and
- the different applicable standards.

If you are interested in taking the CCIBAM course, please visit the website for the Sound Insulation Testing Register Ireland (SITRI) who manage applications for the course, and who can also provide information on the Irish sound insulation testing registration scheme. **https://www.soundtestingireland.com/go/training**

Specialist module on building acoustics in the IOA Diploma

This module is one of four specialist modules from which Diploma candidates choose two, but it can be taken as a standalone module with or without assessment. As well as comprehensive course notes, the blended learning version features eight videos, presented by Dr Juan Battaner-Moro, which cover:

- analysing the acoustical performance of enclosed spaces in buildings;
- building components and structures;
- identifying means of achieving desired acoustical characteristics in spaces;
- predicting noise generated by building services; and
- specifying electroacoustic system requirements for use in buildings.

After completing the module, candidates should be able to identify and select appropriate indices, criteria and standards for assessing the acoustical performance of buildings, formulate an appropriate design protocol in a specific indoor situation, carry out measurements and calculations to justify and implement an acoustical design strategy and write an appropriately structured technical report. For more details visit **https://www.ioa.org.uk/diploma-acoustics-and-noise-control**

Online refreshers

A series of short online refreshers which recycle and repackage videos produced for the blended learning version of the IOA Diploma will be launched in 2023. These online refreshers will be (freely) available to IOA members and do not involve any assessment (self or otherwise). Three of them relate to building acoustics.

Room Acoustics refresher consists of four videos:

- sound absorption, sound absorbers and sound absorption measurement;
- standing waves and room modes;
- room acoustics calculations; and
- aspects of design for good room acoustics including auditorium acoustics.

Sound Insulation refresher has seven videos:

- principles of sound transmission;
- factors that influence sound insulation and ways of improving sound insulation;
- airborne and impact sound insulation measurement;
- sound insulation rating;
- sound insulation in practice covers topics such as robust details, and guidance on relevant considerations in schools and hospitals;
- control of building vibrations; and
- noise from building services.

Vibration refresher has two parts relating respectively to vibration fundamentals and building vibrations.

A new type of certificate?

One of the ideas being discussed concerning the future education and training provisions of the IOA is that of an **advanced certificate**. An example relating to building acoustics would involve a combination of the Certificate of Competence in Building Acoustics Measurement and the Diploma Specialist Module on Building Acoustics. The precise form, assessment provision and delivery modes for the advanced certificate have yet to be determined.

Museum soundscapes

British museums of the late Victorian era were created and designed to house vast collections of artefacts; characterised by expressive volumes and hard reflecting surfaces which result in a cold soundscape. More recently, museums have undergone significant changes in their mission: aiming to become inclusive places for learning and self-development where the emphasis is on the visitor experience.

By Rebecca Romeo Pitone and Jack Harvie-Clark

This article explores how, in conjunction with curatorial practice, acoustic design could reinforce this important shift.

When designing a new type of museum soundscape it is particularly important to consider visitors with hearing and visual impairments, sensory issues, and non-native speakers, as well as those that feel museums are 'not for them'.

We carried out a consultation on behalf of an architectural firm, tasked with the refurbishment of a public war museum in the North East of England.

The museum and its renovation

The Museum was built in the 1960s and its collection includes hundreds of thousands of artefacts, including documents, weapons, uniforms, medals and other war memorabilia.

In 2016, the local authority closed the museum because of low visitor numbers. However, following a campaign led by the local community, this decision was overturned and after a consultation led by the architect, the local authority agreed to restore the venue. The renovation includes an upgrade of the existing building, a purpose-built extension to hold the museum collection, and the redesign of the outdoor area to be turned into a reflective garden. Plans featuring ambitious exhibitions, state-of-the-art educational facilities and a new section dedicated to restaurants are representative of a bigger repositioning plan for the museum within the regional and national cultural landscape.

Due to the grandeur of their architectural design, museums have acquired a distinctive soundscape — we can all picture the imposing ambience of the museum foyer, which warns us about the imminent enforcement of silence. The acoustics in this type of building is reminiscent of that of a place of worship and reinforces the idea of the museum as a 'temple'.

Dr David Fleming, Director at National Museums Liverpool[1], describes how the museum architecture itself functions: *"Many museums were designed to overwhelm visitors. The classical columns and pediments, the banks of steps, the ornate iron gates — these are devices that convey numerous messages, all quite conscious, about what an entry to this grand edifice will lead to. Museum architecture has always been, and still is, an area where pomposity and vainglory can run riot. [...] It is the cavernous interior that often reduces people to hushed whispers and an impression that, somehow, they oughtn't to be there."*

Footnotes

1. D. Fleming, 'Creative space', in Reshaping Museum Space - Architecture, Design, Exhibitions, Ed. London: Routledge, 2005, pp-53-61.

Above: Figure 1. Binaural video of main exhibition room
https://vimeo.com/825782544/e82d07de74

New museums ought to explicitly counteract the impression that their spaces and collections are exclusive to a certain group of people. Questions of accessibility and diversity are at the heart of the new museum, not just as drivers for attendance, but as key values for an institution that needs to reflect change in society. In the new museum, the emphasis must be on the visitor experience and the services required to satisfy their expectations[2]. And, for the visitors who can hear, the museum is not a visual place, but an audiovisual environment[3], therefore their experience needs to be addressed from an aural perspective too.

Our initial task during the consultation was to characterise the desired visitor experience from an acoustic perspective.

The context of museums' soundscapes

ISO 12913-1 defines context as a complex system of *'interrelationships between person and activity and place, in space and time'*[4]. It is context that transforms an acoustic environment into a soundscape. Since museums are cultural venues, context needs to be framed from a cultural perspective. In the full version of this article, we explore the origins of the soundscape of the museum-temple, tracing its connection with colonialism.

If the museum-temple that was designed to overwhelm and intimidate its visitors is a huge, extremely reverberant space where every footstep, whisper and cough is amplified and where the build-up of sounds gets uncomfortable, especially for people with sensory issues, then, these acoustic qualities will carry connotations of exclusion, even when transferred to the new museum.

Acoustics in museums is not a widely researched topic. As mentioned previously, we know that museum-temples were designed to contain vast collections of artefacts; current literature has not yet discussed whether any consideration was given to their acoustic performance.

At this stage of the research, we must assume that the acoustic qualities of the museum-temple are a by-product of its geometry and the materials employed — marble, granite, alabaster etc all contribute to the 'echo chamber' effect[5].

Carvalho et al.[6] studied the difference between the acoustics of 'modern' and 'old' museums. What they define as 'modern' is the museum built later than the mid-twentieth century, whose design is based on reinforced concrete. According to the authors, the modern museum often presents acoustic issues due to reflective coatings, hard floors, high ceilings and very expressive volumes; whereas the 'old' museum is the museum installed in 'historic' buildings; which, based on their definition of 'modern' could be anything before the mid-twentieth century. Carvalho et al. state that older museums tend to behave better acoustically, compared to modern museums.

A big acoustic challenge when it comes to museums is to create an environment that allows quiet contemplation without preventing the visitors from talking with other visitors or museum staff.

In the preliminary investigation we contrasted two types of museum soundscapes: the first, linked to the museum-temple, is characterised by more reverberant conditions (based on our perception, not measurements in-situ). It is quite common to refer to this environment as 'cold'[7]; since every little sound is magnified against an overall silent background, the attention can suddenly be drawn to us; the experience in these rooms can be quite alienating, especially for people who are not regular museum-goers.

An example of this environment can be heard in this binaural video (at Figure 1) recorded in the main exhibition room of an art gallery in the North East. P26

Footnotes

2. P.C. Marani, R. Pavoni, Musei — Trasformazioni di un'istituzione dall'età moderna al contemporaneo. Venezia: Marsilio Editore, 2006, p. 59.
3. S. Voegelin, 'Soundwalking the Museum — A Sonic Journey through the Visual Display', in The Multisensory Museum - Cross-Disciplinary Perspectives on Touch, Sound, Smell, Memory and Space, Ed. Plymouth: Rowman & Littlefield, 2014, pp. 119-130.
4. BS ISO 12913-1:2014 — Acoustics — Soundscape Part 1: Definition and Conceptual Framework, London: ISO, 2014.
5. Asi Architectural, 'Acoustics In Museums: The Science Of Sound, 2020. [Online]. Available: **https://www.asiarchitectural.com/acoustics-in-museums/**. [Accessed: 24-Apr-2023].

6, 7. A.P. Carvalho, H. Gonçalves, L. Garcia, 'Acoustics of Modern and Old Museums', in NOISE-CON 26/28 Aug 2013, Denver, Colorado. [Online]. Available: **https://www.researchgate.net/publication/263564828_Acoustics_of_Modern_and_Old_Museums**. [Accessed: 27-Apr-2023].

We can immediately notice that the acoustics are not appropriate for the activity being carried out and the overall soundscape is rather cold.

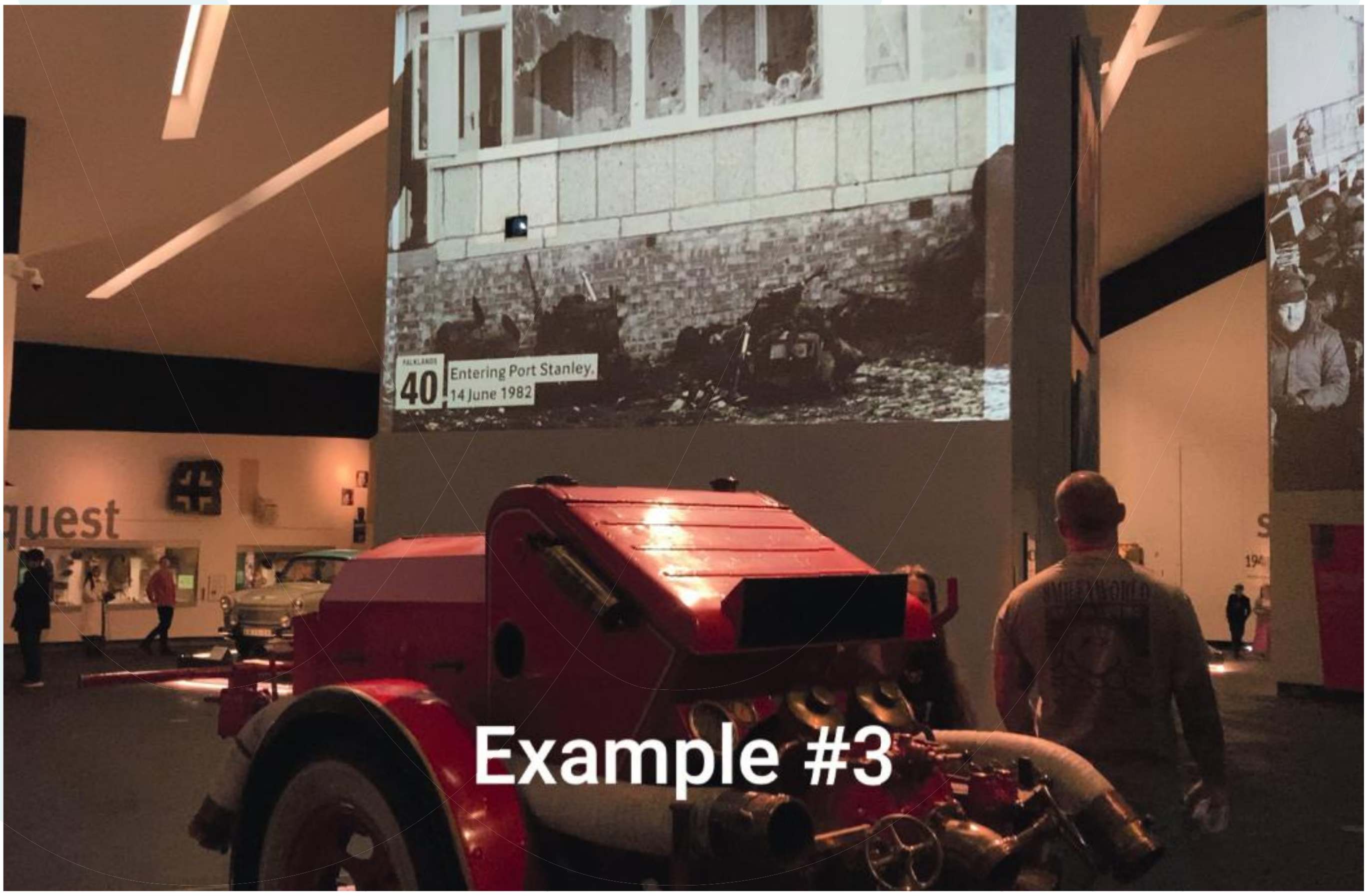
On the other end of the spectrum, this binaural video (at Figure 2) shows an example of a museum space that was designed to host multimedia installations, as well as traditional exhibitions. Here, despite the expressive volumes and the darker colour palettes, the space feels 'warm'.

Inclusive museum soundscapes

To obtain a space like this, which is almost conceived as a walk-in cinema, acoustics needs to be carefully designed. The understanding of accessibility is rapidly changing and the role that the built environment plays in the exclusion of people is getting more widely recognised[8]. Our consultation for the museum drew from recent scholarship and government guidance, (PAS6463)[9] aimed at designing inclusive buildings. One of the main aspects that is considered in this literature is reverberation control. Reverberation typically affects acoustic comfort negatively; it causes background noise to rise and reduces speech intelligibility. Longer reverberation times make listening very tiring for people with a hearing impairment and non-native speakers; while also making orientation difficult for people with a visual impairment. People with neurodegenerative conditions, such as dementia, and neurodivergent conditions (autism, ADHD, dyspraxia) and people with hearing differences, such as hyperacusis and misophonia, are often extremely sensitive to noise. For individuals with high and hypersensitivity, higher background noise can increase stress levels, cause anxiety and ultimately sensory overload[10].

PAS6463 goes into detail about the practical solutions for inclusive design. These include:

- isolating the quietest areas from the noisiest areas, allowing a gradual transition to and fro;



Above: **Figure 2.** Binaural video of contemporary museum. **https://vimeo.com/825785665/de674f5977?share=copy**

Footnotes

8. A. Heylighen, G. Vermeir, M. Rychtáriková, 'The Sound of Inclusion: a case study on acoustic comfort for all', in Designing Inclusive Features, ed. London: Springer, 2008, pp. 75-84.

9, 10. BSI, PAS 6463:2022, Design for the mind - Neurodiversity and the built environment - Guide, London: BSI Standards Limited, 2022.

- background noise level control;
- avoiding hard reflective surfaces, favouring soft furnishings, and providing the correct amount of absorption;
- creating smaller semi-enclosed spaces within a big area; and
- enabling the building users to change their acoustic environment, e.g. switching fans on or off, closing and opening windows, moving from space to space, accessing quiet rooms, choosing the level of noise of an appliance.

This level of control may be difficult to obtain in a museum, where the visitor experience is always mediated (by security and other museum staff); however, emphasis can be placed on the ability to access quiet areas when needed. It is therefore important to make a variety of spaces available and easily accessible to visitors.

Another aspect that may be difficult to implement from a curatorial perspective, is the creation of smaller spaces within an open area; different artefacts from the same collection are usually shown in the same room for narrative purposes.

Conclusion

A warm and inviting soundscape puts the emphasis on the visitor's experience and it can help reduce the museum's threshold fear, i.e. *'the physical [and programmatic] barriers that make it difficult for the uninitiated to experience the museum'*. It reinforces the shift from the museum-temple, to the new, welcoming and inclusionary museum.

There could be a correlation between a warm soundscape and an improved visitor experience. From a commercial perspective, this would imply that acoustic design may have a role to play when it comes to repositioning museums during their refurbishment; changing them from obsolete museum-temples to welcoming, multilayered and inclusive cultural attractions.

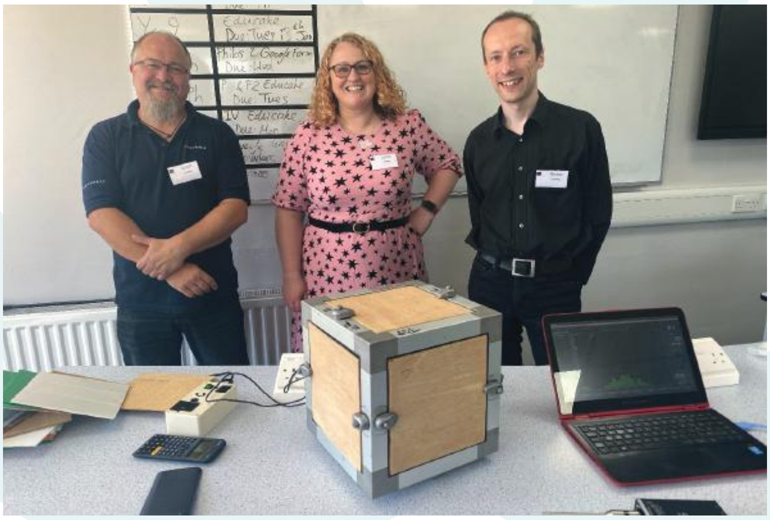
Links

This article is an adaptation of a research paper titled *Decolonising Museum Soundscapes* (by Rebecca Romeo Pitone and Jack Harvie-Clark), submitted to the Forum Acusticum 2023 Torino, Session A14-01 Indoor Soundscaping.

Inspiring the next generation of building acousticians

When talking to young people (and adults) about careers in building design, most tend to think of architects and builders – they may think of civil and structural engineers, but it is unlikely that they will think of acoustic consultants. This highlights the importance of promoting the subject to the next generation to attract the best talent and drive the future of sound in our indoor spaces. STEM ambassador and acoustician, Vicky Wills explains how she does it.

By Vicky Wills



Above:
Andy Waring, Vicky Wills and Matt Muirhead at St Oscar Romero School with the 'You're Banned!' activity

The acoustic design of a building is important for the people that use it. For example, people that live in a building need to be able to relax and enjoy their home without worrying about noisy neighbours and next door's dog!

Offices are designed to aid concentration, schools to encourage collaboration, and music venues to make every hair on the back of your neck stand on end when your favourite musicians take to the stage! Every story is different, and acousticians decide how that story sounds.

I am an acoustician. I am also a STEM (science, technology, engineering and maths) ambassador, which means I take a special interest in communicating the importance of sound and acoustics in the built environment.

I'm going to share some examples of how we communicate building acoustics to young people, including a couple of activities that are interactive, engaging and transferable across learning abilities.

The importance of a good demonstration

I went to my first careers fair as a STEM ambassador, at a local school about 10 years ago. I took what I could find from my office and my laptop. A few people stopped at my table, but I certainly wasn't rushed off my feet. I was thinking, "I know that acoustics is really interesting, so why won't anyone talk to me?"

On the other side of the room was a stand with a constant buzz. They had a really cool demonstration that involved mixing water, tiny bits of paper and polystyrene balls in a big tank. The demonstration involved altering the shape of the tank with inserts which totally changed how the objects in the water moved — it was mesmerising! The people at that stand watched the demonstration and stayed to ask questions. So, since that first careers fair, I have always strived to demonstrate the most engaging and interactive concepts of acoustics as playfully as I can.

Acoustic demos and making the most of the venue

There are plenty of great, simple and cheap sound demonstrations that can be used when talking to people about sound. This includes:

- videos of real places and spaces; from train stations to anechoic chambers;
- recordings of the same sound in different real and theoretical spaces;
- musical instruments and talking about how they were designed to amplify sound;
- music boxes or vibration speakers to demonstrate structure-borne vibration;
- sound delay experiment on the school grounds; and
- discussions of soundscapes and soundwalks.

These types of quick demos work well in classroom settings, are useful for any age group and ability and can easily fire up a student's imagination.

However, careers fairs are generally set up in large open rooms (like a sports hall) with lots of reflective surfaces. Generally, all surfaces are acoustically hard and reflective, which is great for bouncing balls in, but is not an ideal space for speech. Sound and audio demonstrations (apart from ear defenders) generally don't work well in these large, noisy rooms. You'd have thought we would have cracked this problem by now, but alas...demonstrating acoustics in a noisy environment is hard work!

Nevertheless, we can use the space we are in to our advantage when explaining what acousticians do for a living. Why does it sound terrible? Why can't we hear the teacher when they turn their head away from us? Is there anything in the room that was designed to improve the acoustics? How does the sound differ from other spaces, like libraries and swimming pools? Would the room sound different if bigger or smaller? What kind of things could we do to improve the sound in that space? A sports hall is a great space to think about the importance of acoustic design.

But, a lovely conversation about the room we are in isn't going to draw a crowd, so what can we put on a careers table to create some buzz about our stand?

Some very lucky acousticians might have access to something that makes sound visual, like an acoustic camera, a visual sound limiter device, or even something like a head and torso simulator. We could use our laptop screen and a pair of headphones to run some demos, but without a dedicated colleague to help, hunching over for two hours is a recipe for backache, and any technology issues could take attention away from valuable conversations.

I appreciate that so far nothing I have said is looking very promising for careers fairs, and STEM ambassadors must just chuck some leaflets, mugs and pens into a carrier bag and hope for the best...but hold on a bit longer, I might have the answer...

My favourite acoustic crowd pleaser

Almost everything that acousticians do to make spaces sound better is because of what we hear through our ears. So...let's use the room we are in to run quick listening experiments. So much of our world today is virtual, so we can do something real, fun, memorable... and a bit silly.

Hopefully, with enough time before an event to get to a hardware shop, we can create a few easy demos using cheap ear defenders, plastic waste pipes and (sometimes) funnels. This includes:

- confusaphones (swapping ears);
- ear funnels (amplifying sound from one direction);
- making seashell sounds;
- the swanee whistle (making a penny whistle that uses ambient sound); and
- musical pipes.

The instructions to make them are here
http://salfordacoustics.co.uk/listening-devices/.

As well as being great experiments that work well in busy rooms, they are eye-catching, and people like to take pictures of themselves looking daft. This isn't a perfect fit for room acoustics, but the devices actually work BETTER in busy rooms, so that's something else that we can discuss with the students. P30

Above:
Alex Krasnic wearing confusaphones at the Big Bang Fair South East 2019

If you don't work in acoustics but still carry out school engagement, I recommend taking something hands-on and fun along that is related to your job. It could involve dry spaghetti and marshmallows, foil, marbles and a tank of water or even Lego, but it's a great way to get people to visit your table, and stay for a chat. STEM is about opening doors in education, engaging, inspiring and communicating.

In addition to something fun, it is a good idea to have a tablecloth, a banner, some relevant leaflets and links/ QR codes. (Maybe even some freebies, if you have any). Although really, the most important thing at a careers fair is you, the enthusiastic role model, talking about your career.

You're Banned! – classroom activity

There is one more exciting resource that I haven't yet mentioned, which can be used in classrooms by IOA members. The IOA owns and maintains the 'You're Banned!' classroom activity that asks groups of pupils to design and maintain their own soundproof practice room for a band or music group.

Each group is given a test rig comprising a framework for the room into which they can fit a range of materials of differing density and absorption characteristics such as foam, sheet steel, plywood, hardboard and plastic. The students are also provided with a sound source, representing most of the instruments, and a vibration source, representing the drum set. The aim is to design the room in such a way as to minimise the airborne and structure-borne sound transmission within a given budget.

This hands-on activity allows the students to investigate and experience acoustic principles, by testing and improving their design, which is far more fun, valuable and memorable to the students than sitting through a long presentation!

The activity is a great introduction into the principles of building acoustic design and can be a focal point for the discussion of a wide variety of topics from façade design to flanking transmission and dampening within building structures.

For more information about the 'You're Banned!' kits, please contact **stem@ioa.org.uk** .

Plans for 2023

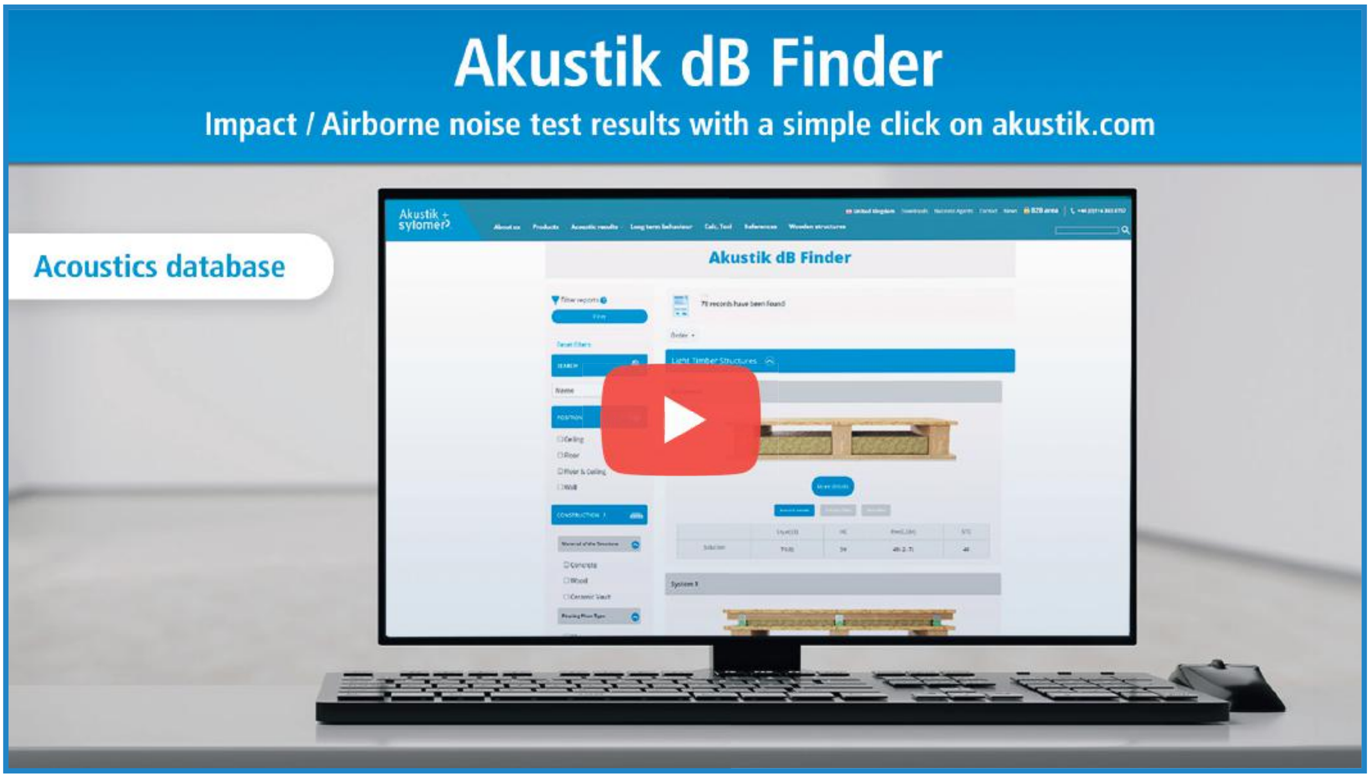
Springpod will be working with the IOA again in 2023 to deliver the virtual work experience on acoustics to young people. The programme will be accessible all year round so attendees can fit it around their school work, exams and holiday periods. Please tell the young people in your life to sign up here **https://tinyurl.com/66ktscr4** . ◎

This article should remind you that:

- There are plenty of great, simple and cheap sound demonstrations that can be used when talking to people about sound.
- Create a few easy demos using cheap ear defenders, plastic waste pipes and funnels.
- If you don't work in acoustics but still carry out school engagement, take something hands-on and fun along to a careers fair that is related to your job.

Springpod partners with universities and employers to create interactive, experiential learning programmes which empower the next generation and enable them to take their future into their own hands by giving them equal access to opportunity.

AMC MECANOCAUCHO UK



Our **expertise** lies in the **building and industrial acoustics** field.
We have a dedicated **technical department** with skilled engineers who are available to assist with solutions to meet your project requirements.

GET ACCESS

Don't hesitate to **get in touch with our main office or explore our websites** and social media platforms.

YouTube in

Lewis Metcalf
Applications Engineer – UK & Ireland

+44 (0)752 311 8007
lewis.metcalf@amcuk.co.uk
Leicester, UK
www.amcuk.co.uk
www.akustik.com

Pardon? What? Huh?

Following the STEM article on the previous two pages, we now explore the concepts of reverberation time and speech intelligibility – both fundamental in the acoustic design of buildings, and suggest ways we can experiment with acoustics at home, school or anywhere else!

By Cameron Salisbury, Senior Acoustics Consultant, Environment, Europe & India, AECOM

Above: Clapping your hands is a fantastic way to estimate a reverberation time

Acoustics is an important consideration in building design because it can greatly impact the overall experience of a space, especially an indoor space.

Imagine being in a school hall with poor acoustics, where the sound echoes and reverberates, making it difficult to understand someone speaking at the front. A well-designed space with good acoustics controls these sound reflections and can enhance a performance, improving the overall audience experience.

Reverberation time

Reverberation could be described as 'leftover sound'. It's what you hear after an initial sound has stopped, like a balloon popping. It's the 'pshhhhhhhht' you hear after you clap your hands in a tunnel – the sound that seemingly lingers just that little bit longer. This lingering sound is all the reflections of sound that still have enough energy to travel and have not already been absorbed by surfaces or materials in the space. Acousticians say "RT60", which means 'ReverberationTime60dB'. This is the time taken for a sound to decay by 60 decibels (dB) after the initial sound has stopped. Well spotted, 60dB is the (60) in RT60! Of course, an RT30 would be the time taken for a sound to decay by 30dB... and so on and so on... Easier than it soooouunndss...right? In other words, reverberation time is the time it takes for sound to 'fade away'.

Long reverberation times cause sounds to echo and linger, making it difficult to understand speech and music. This often happens in large open spaces like churches or auditoriums, where the sound can bounce off hard surfaces and reverberate for several seconds. On the other hand, a room with a short reverberation time will have a more controlled sound, making it easier to understand speech and music. This is often the case in smaller rooms or spaces with sound-absorbing materials, like carpet or acoustic panels. Don't believe me? Clap your hands in your bedroom or living room and then again in the bathroom or kitchen – you should hear a difference. Reverberation time is affected by the size and shape of a room, as well as the materials used for the walls, ceiling, and floor.

Speech intelligibility

Speech intelligibility is the measure of how well and clearly speech can be heard and understood in all parts of any given space. It is affected by reverberation time (and therefore size, shape, materials present etc. within a room), background noise, and the quality of a sound system (if there is a sound system present). In general, the goal is to design a space with high speech intelligibility, where speech can be easily understood by listeners. For example, at a railway station, it is important to be able to hear announcements like 'the next train arriving on platform 1 is the...' you get the idea. But there are times where privacy is desirable too and spaces such as restaurants or open plan offices are designed to have lower speech intelligibility so that neighbouring conversations become more private.

To achieve high speech intelligibility, designers must consider the acoustics of the space and select appropriate absorbers (to stop sound reflecting), diffusers (to encourage sound to scatter in different directions as it reflects) and sound system placements.

Right: Reverberation could be described as 'leftover sound'. It's what you hear after an initial sound has stopped, like a balloon popping

For example, in a lecture hall, it is important to minimize background noise and reverberation time (high absorption), while also ensuring that the sound system is correctly positioned to produce high quality sound and is also properly calibrated.

Experimenting with acoustics

Understanding reverberation and speech intelligibility can help us appreciate the importance of good acoustics in building design. If you are interested in experimenting with acoustics, here are a few simple things you can try at home or in a classroom:

Clapping your hands is a fantastic way to estimate a reverberation time. Clap your hands once in a bathroom or somewhere with hard or tiled surfaces. You should hear that there is some reverberation (lingering sound after the clap). Try adding sound-absorbing materials, like pillows and blankets...clap your hands again. Do you notice a decrease in reverberation as you add more sound-absorbing materials?

You should notice the sound is more controlled and doesn't echo so much. If it does, why do you think that is? Remember, the size, shape and construction materials all contribute to the acoustics of a space. Could you position your absorbers more effectively?

Fade out

Experimenting with acoustics can give us a better appreciation for the importance of good acoustics in our daily lives. Whether we are attending a lecture, watching a film, or simply listening to music, the acoustics of a space can greatly impact our overall experience.
By understanding concepts like reverberation time and speech intelligibility, we can begin to design and create spaces that are both functional and enjoyable to be in. So start clapping your hands more and figure out why certain spaces sound the way they do.

Fun fact: The longest recorded reverberation time is 112 seconds!

In 2014, acoustics expert Trevor Cox crawled through a narrow pipe into a subterranean oil tank in Inchindown, Scotland. One gunshot and 75 seconds later, he had set a new world record for the longest echo in a man-made structure. Learn more about reverberation time, and listen to the record-holding gunshot in the underground chamber here: **https://www.bksv.com/en/knowledge/blog/perspectives/longest-reverb**

Guide to commonly-adopted building acoustics standards and guidance documents

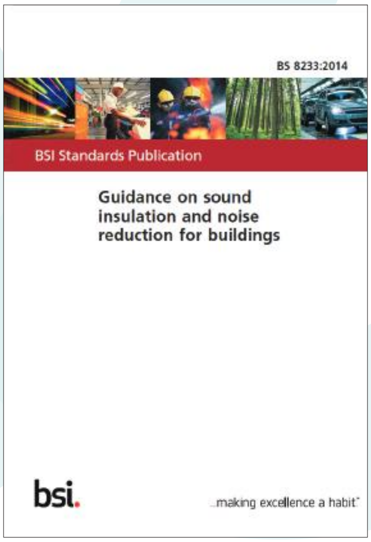
In this article, we take a close look at some of the most commonly-adopted sources of building acoustics criteria which acousticians may typically reference at the early design stages of a project.

By Alex Krasnic

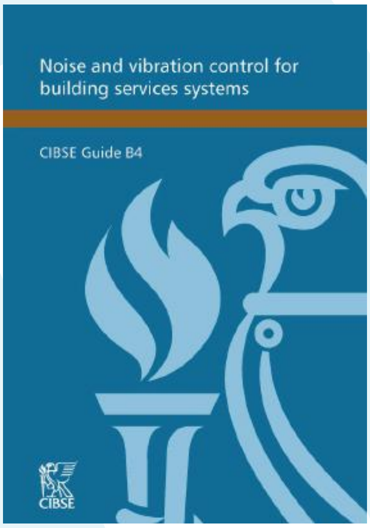
Because building types/uses are so numerous and potentially feeding from a multitude of sources of acoustic performance criteria, a selection of typical built environment sectors are referenced below, each identifying the most common sources (some of which may be utilised across multiple sectors). To conclude, a selection of commonly adopted environmental and sustainability certification schemes are also referenced, with particular focus on building acoustics requirements.

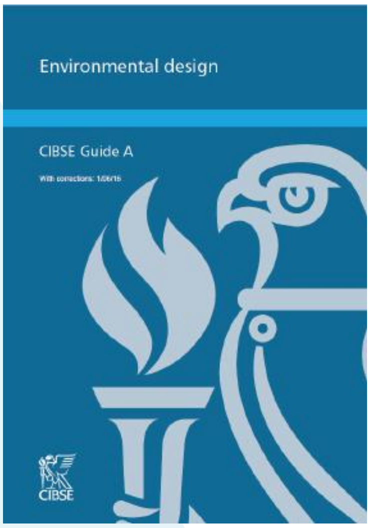
Multi-sector

The single, most commonly referenced multi-sector standard (certainly on UK-based projects) is British Standard; *BS8233*. Now in its 2014 edition, BS8233 has been around since its first 1978 edition, with its origin tracing back to 1972 when it was first published as *P:3 Chapter III:1972*. An important aspect of BS8233 is explained in the 2014 edition Foreword: *BS 8233:1999 was, like its predecessor CP3 Chapter III:1972, published as a code of practice. However, it was decided to publish this edition as a guide because the text largely comprises guidance that does not support claims of compliance*. Excepting this nuance, the primary reason for its ubiquitous adoption on projects, is due to its inclusion of recommended internal sound level targets (a set of criteria referred to as 'internal ambient noise levels' (IANLs)) for a multitude of different buildings/ space uses. Specifically, BS8233 contains IANL guideline noise levels for spaces such as department stores and canteens/kitchens through to libraries/galleries and museums, as well as office spaces and places of worship and meditation/relaxation.

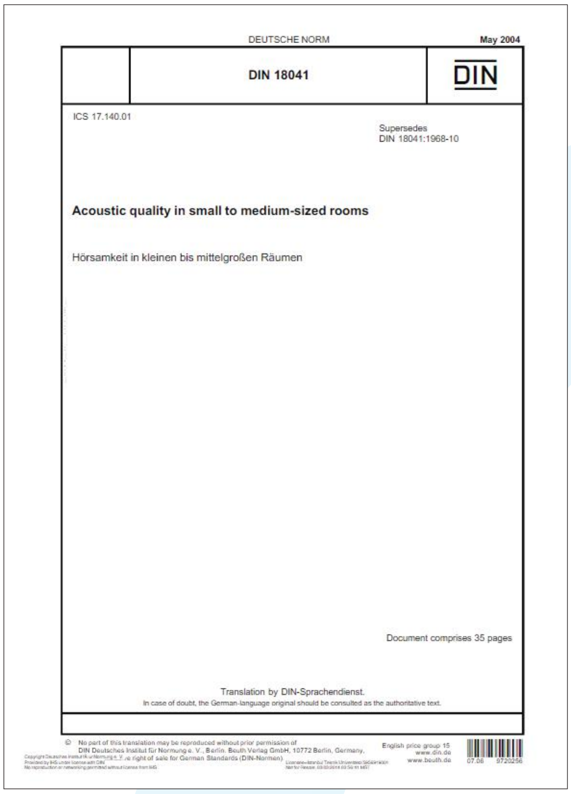


Its most referenced inclusions perhaps, are the guideline IANLs provided in Table 4 dedicated to residential spaces in dwellings notably; bedrooms, living rooms and dining areas with recommended targets for both daytime and night-time periods, adopting both the $L_{Aeq,T}$ (dB) and $L_{Amax,F}$ (dB) (footnoted) noise metrics, which are commonly stipulated in numerous local authority planning conditions. Other uses of BS8233 include definitions of common acoustic metrics/indices such as; 'Weighted Sound Reduction Index (R_w), Reverberation Time (T) Standardised Impact Sound Level ($L'_{nT,w}$) and the Weighted Standardised Level Difference ($D_{nT,w}$) the latter of which is adopted in Table 3 of BS8233, which provides recommended airborne sound insulation (SI) performance criteria for separating elements (such as floors and partitions) based on the activity in the 'source' room and the privacy requirement and noise sensitivity of the 'receiving' room. Finally, BS8233 also provides useful guidance on typical separating wall and floor constructions to achieve various laboratory-rated airborne SI performances in Annex E, information on sound-absorbing materials in Section 7.7, as well as guidance on internal noise criteria for vertical transportation and building services systems (including usage of the Noise Rating (NR) metric).





Another source of common multi-sector acoustic design guidance comes from the Chartered Institute of Building Services Engineers (CIBSE). Over numerous decades, CIBSE has published its set of guides, which comprise a collection of design guidance and recommended performance criteria for a multitude of building services systems that may be specified for different buildings/ spaces. Of primary importance to building acoustics are two parts of the CIBSE Guides. Guide A *Environmental Design* presents Table 1.5 which recommends a set of comfort-based noise criteria for specific applications again, adopting the NR metric. A key feature of the NR criteria which are presented in this table, is that acoustic criteria are provided for almost 100 different internal space uses (and subgroups of building types) offering building acousticians a wide range of building services noise criteria to consider. The second CIBSE document is Guide B4 *Noise and vibration control for building services systems*, the key features of which include typical insertion losses (attenuation values) for different configurations of in-duct attenuators (rectangular or circular and 'lined' or 'unlined') as well as guidance on limiting duct velocities in various ventilation duct elements to achieve a stated roomside NR criterion, as well as vibration isolation criteria (including minimum static deflections) for a multitude of common building services systems each identified with recommended isolation types.



DEUTSCHE NORM May 2004

DIN 18041 DIN

ICS 17.140.01

Supersedes DIN 18041:1968-10

Acoustic quality in small to medium-sized rooms

Hörsamkeit in kleinen bis mittelgroßen Räumen

Document comprises 35 pages

Translation by DIN-Sprachendienst.
In case of doubt, the German-language original should be consulted as the authoritative text.

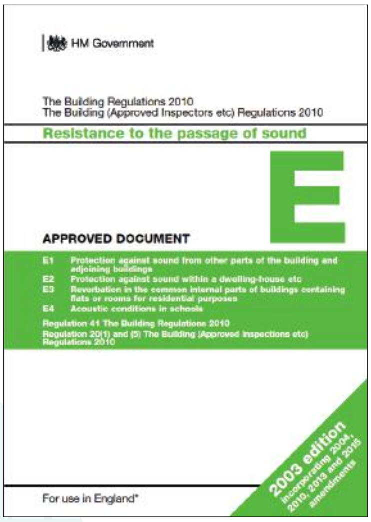
© No part of this translation may be reproduced without prior permission of DIN Deutsches Institut für Normung e. V., Berlin. Beuth Verlag GmbH, 10772 Berlin, Germany, has the exclusive right of sale for German Standards (DIN-Normen).

English price group 15
www.din.de
www.beuth.de
07.06 9720256

The final multi-sector acoustic design guidance (perhaps less frequently encountered) doesn't originate from any UK-published sources but actually from the German DIN Standards. DIN 18041 *Acoustic quality in small to medium-sized room* (trans.) originally published in 1968. Whilst not recommending any room acoustic criteria in the early editions, since the 2004 version (and retained in the current 2016 edition), a set of useful Reverberation Time (T, seconds) criteria for different space uses and room volumes (in cubic metres) are presented, notably for 'Category A' spaces (acoustic quality for 'medium' and 'long'-sized rooms). For Category B spaces (acoustic quality for 'short'-sized rooms) the five subdivided space types are given recommended ratios between the room absorption area (A) and the room volume (V) with indicative room heights (h) to provided suitable reverberation control (specifically for speech communication, in the acoustic frequency range; 250 Hz to 2 kHz).

Residential

Where residential schemes are concerned (new builds or changes of use), three key sources of acoustic performance criteria can be found in the Building Regulations 2010. These being the following statutory instruments: Approved Document, Part: E *Resistance to the passage of sound* (2003 edition, incorporating 2004, 2010, 2013 and 2015 amendments) (ADE), Approved P36


HM Government

The Building Regulations 2010
The Building (Approved Inspectors etc) Regulations 2010

Resistance to the passage of sound

E

APPROVED DOCUMENT

E1 Protection against sound from other parts of the building and adjoining buildings
E2 Protection against sound within a dwelling-house etc
E3 Reverberation in the common internal parts of buildings containing flats or rooms for residential purposes
E4 Acoustic conditions in schools

Regulation 41 The Building Regulations 2010
Regulation 20(1) and (5) The Building (Approved Inspectors etc) Regulations 2010

2003 edition incorporating 2004, 2010, 2013 and 2015 amendments

For use in England*


HM Government

The Building Regulations 2010

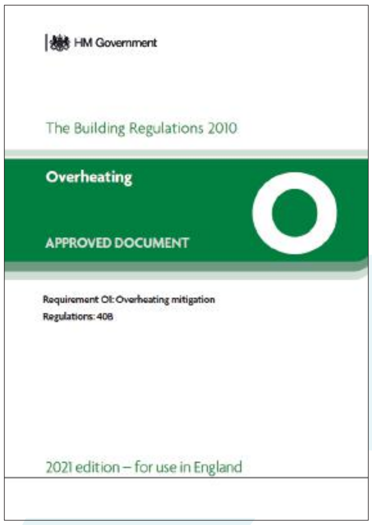
Ventilation

F

APPROVED DOCUMENT

Volume 1: Dwellings
Requirement F1: Means of ventilation
Regulations: 39, 42 and 44

2021 edition – for use in England


HM Government

The Building Regulations 2010

Overheating

O

APPROVED DOCUMENT

Requirement O1: Overheating mitigation
Regulations: 40B

2021 edition – for use in England

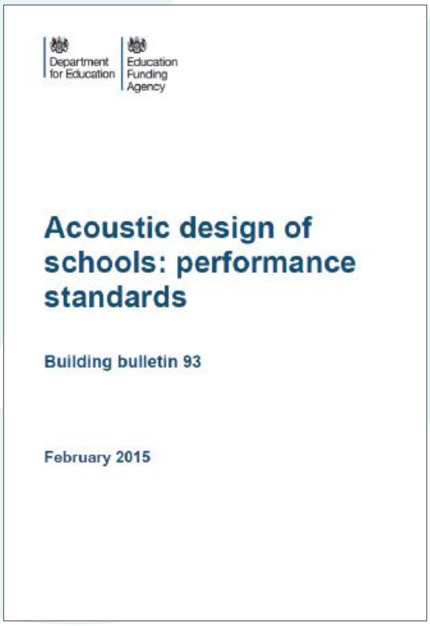
Document, Part: F1 *Ventilation, Volume 1: Dwellings* (2021 edition) (ADF) and Approved Document, Part: O1 *Overheating mitigation* (2021 edition) (ADO) each containing important acoustic criteria.

Critically, of the three, are the minimum sound insulation (airborne and impact) performance requirements stipulated under Part E1 of ADE intended to provide a reasonable resistance to the pasage of sound within houses, flats and 'rooms for residential purpose' (e.g. care homes and student accommodation). Tables 0.1a (Dwelling houses and flats) and 0.1b (Rooms for residential purpose) stipulate the minimum performance criteria for walls, floors and stairs which provide a separating function as means of complying with the directive of Part E1. Airborne criteria (walls and floor/stairs) are given in terms of the $D_{nT,w} + C_{tr}$ (dB) metric and impact criteria (floors only) given in terms of the $L'_{nT,w}$ (dB) metric.

Additionally, Table 0.2 of Part E2 stipulates an airborne performance requirement for internal walls and floors, as means of providing a reasonable resistance to the passage to the passage of sound within (the same) residential dwellings. Part E3 provides acoustic performance requirements to control reverberation within communal areas (e.g. corridors, hallways, stairwells and entrance halls, which provide access to flats or rooms for residential purpose). Section 7 details two methods; Method A (a more general method) and Method B (a more flexible method) for calculating the minimum acoustic absorption required in these spaces, to demonstrate compliance with Part E3.

While ADF stipulates minimum ventilation requirements and means of controlling external pollutants in residential dwellings, selected acoustic performance criteria are also provided. Specifically, with regards to noise generated by mechanical ventilation systems (including both continuous and intermittent operation), Sections 1.5 to 1.7 provide useful criteria for such systems (which share some overlap with other guidance, e.g. CIBSE Guide A and BS8233).

Lastly, the recently-introduced ADO provides acoustic performance requirements when mitigating the overheating condition, but with a limited remit covering bedrooms during the night-time period (i.e. 23.00 to 07.00 hrs daily) and for new-build residential developments only. Introducing two compliance methods (a *Simplified method* and a *Dynamic thermal modelling method*), Part 01(2)(a) of the approved document introduces the dynamic thermal modelling method, to further susbstantiate (by detailed assessment) that mitigating the overheating condition by means of openable windows, can be precluded. By providing limiting internal ambient noise criteria for bedrooms (during the night-time) under Clauses 3.2 to 3.4, the allowable maximum free area to achieve the acoustic requirements can inform the dynamic thermal modelling (which also needs to comply with CIBSE TM59). Alternatively, the minimum free area to satisfy thermal modelling requirements can be reviewed by acousticians to determine whether the internal noise criteria would be achieved.


Department for Education | Education Funding Agency

Acoustic design of schools: performance standards

Building bulletin 93

February 2015

Education

With regards to education schemes (primary and secondary schools in particular), Part E4 of Approved Document, Part: E (see residential above) actually stipulates the minimum acoustic conditions required for schools. Section 8 of ADE enforces this by effectively signposting the means to compliance with Part E4 by achievement of the performance requirements given in *Building Bulletin 93: Acoustic design of schools* (BB93).

While BB93 has seen numerous revisions over the years, version 17 of the February 2015 version currently stands as the legislated edition to demonstrate compliance with Part E4 of ADE (exempting admin/ancillary areas, nurseries, colleges, HE and FE establishments (including universities), as well as community and adult education facilities). The key acoustic performance standards provided in BB93 include; limiting IANL criteria (in terms of the $L_{Aeq,30\text{-}mins}$ (dB) metric) for various internal spaces, a rain noise criterion for roofs, as well as limiting noise performance values for ventilation (including purge) and cooling equipment, airborne SI performance criteria for separating walls and floors (also in terms of the $D_{nT,w}$ (dB) metric), as well as for corridors (with or without doors) (in terms of the laboratory-rated R_w (dB) metric) and through-wall ventilators (in terms of the $D_{n,e,w}$ (dB) metric), impact SI performance criteria for floors (also in terms of the $L'_{nT,w}$ (dB) metric) and reverberation time criteria (in terms of the T_{mf} (mid-frequency RT, seconds) metric).

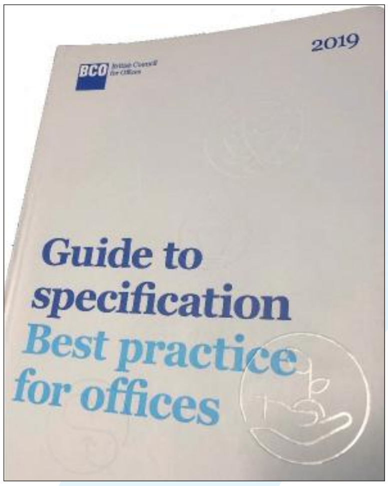
Additionally, while not mandated under compliance of Part E4 of ADE, a set of Speech Transmission Index (STI) criteria are provided, relative to instructional or critical listening activities (within or between, groups) to satisfy the requirements of the School Premises Regulations (SPRs), the Independent School Standards (ISSs) and the Equality Act.

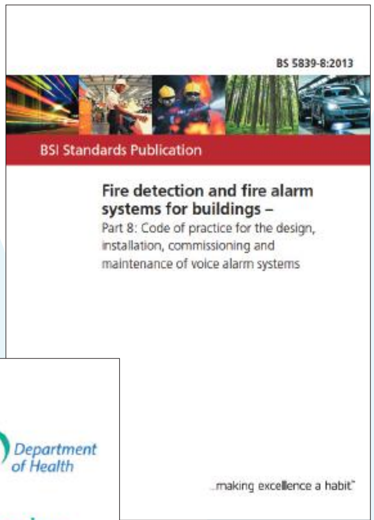
Healthcare

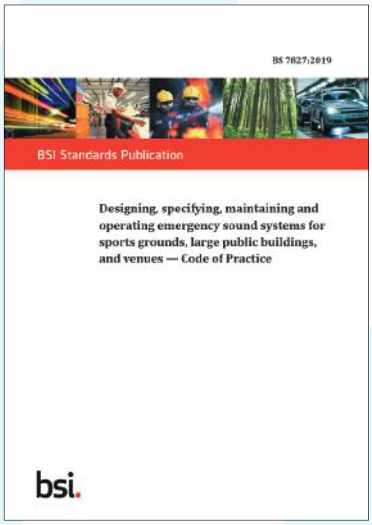
With regards to healthcare projects, the Department of Health stipulates that facilities shall be designed in accordance with the requirements set out in Health Technical Memorandum; HTM:08-01. Since this document replaced its predecessor; HTM 2045 in July 2008, HTM:08-01 is intended as an acoustic design compliance document for state funded healthcare facilities, and is occasionally also referenced on privately funded projects. In principle, HTM:08-01 provides a similar breadth of acoustic design criteria as that contained in BB93.

Offices

Relative to office developments (and typically on UK-based projects), the acoustic design criteria contained in the British Council of Offices (BCO) Guide to Specification (GtS) may commonly be adopted. BCO GtS contains periodically updated performance criteria for numerous office building functions, with the Acoustics section of the latest edition (June 2019) containing appropriate design criteria for different types of office spaces.





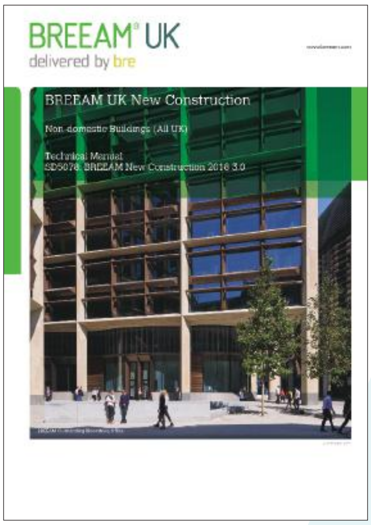


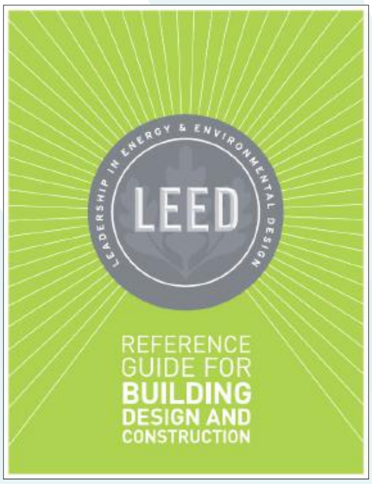
Sport and leisure

While most of the acoustic design criteria contained in BS8233 may broadly be applicable to sport and leisure-based projects, additional acoustic performance guidance can also be found relative to the function of reinforced sound systems (including those specified for life safety applications) within both British Standards; BS5839-8:2013 and BS7827:2019. Where a Voice Alarm System (VAS) is required to broadcast speech-based messages, BS5839-8 recommends minimum signal-to-noise ratio performances, as well as RT and STI requirements to ensure appropriate clarity and speech intelligibility, all of which influence the acoustic design of relevant spaces. Similarly, BS7827 also provides acoustic design criteria relative to appropriate RT and IANL performances for spaces containing emergency microphones. P38

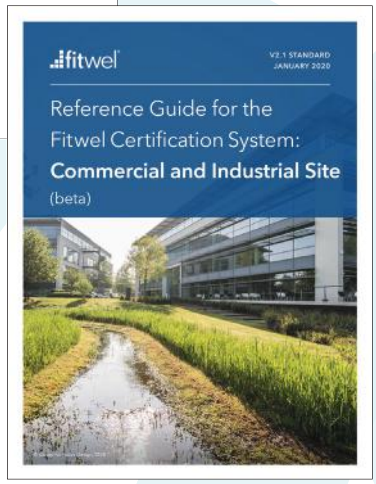
Sustainability and environmental certification scheme

Lastly, a selection of sources of sustainability and environmental certification scheme criteria are presented in this section. The most-commonly adopted environmental certification scheme on UK-based projects (some 535,000 buildings having been certified (globally) since its launch in 1990) is the Building Research Establishment's (BRE Group) *Environmental Assessment Method* (BREEAM). In almost all current BREEAM Technical Manuals (ranging from 'New Construction (Non-domestic)', (as illustrated) to 'International New Construction') two primary performance categories will influence the acoustic design of buildings certified under this scheme. The first being *Health & Wellbeing: Acoustic Performance* (Hea 05), and the second being *Pollution: Reduction of noise pollution* (Pol 05), both of which contain a set of acoustic performance requirements (often referencing other acoustic standards presented in this article, e.g. BS8233) which different types of buildings (and internal spaces within) are required to achieve, to evidence the award of available credits towards the global scheme certification score.





More commonly adopted on international built environment projects (but increasing in popularity in the UK) the U.S. Green building Council's *Leadership in Energy and Environmental Design* (LEED) certification scheme goes a step further than BREEAM by providing its own bespoke set of acoustic performance criteria (as opposed to referencing those from established guidance documents). LEED requires specific acoustic performance requirements (affecting the wider building design process) to be demonstrated in line with appropriate occupant health and wellbeing outcomes, and for a variety of different building types/space uses.



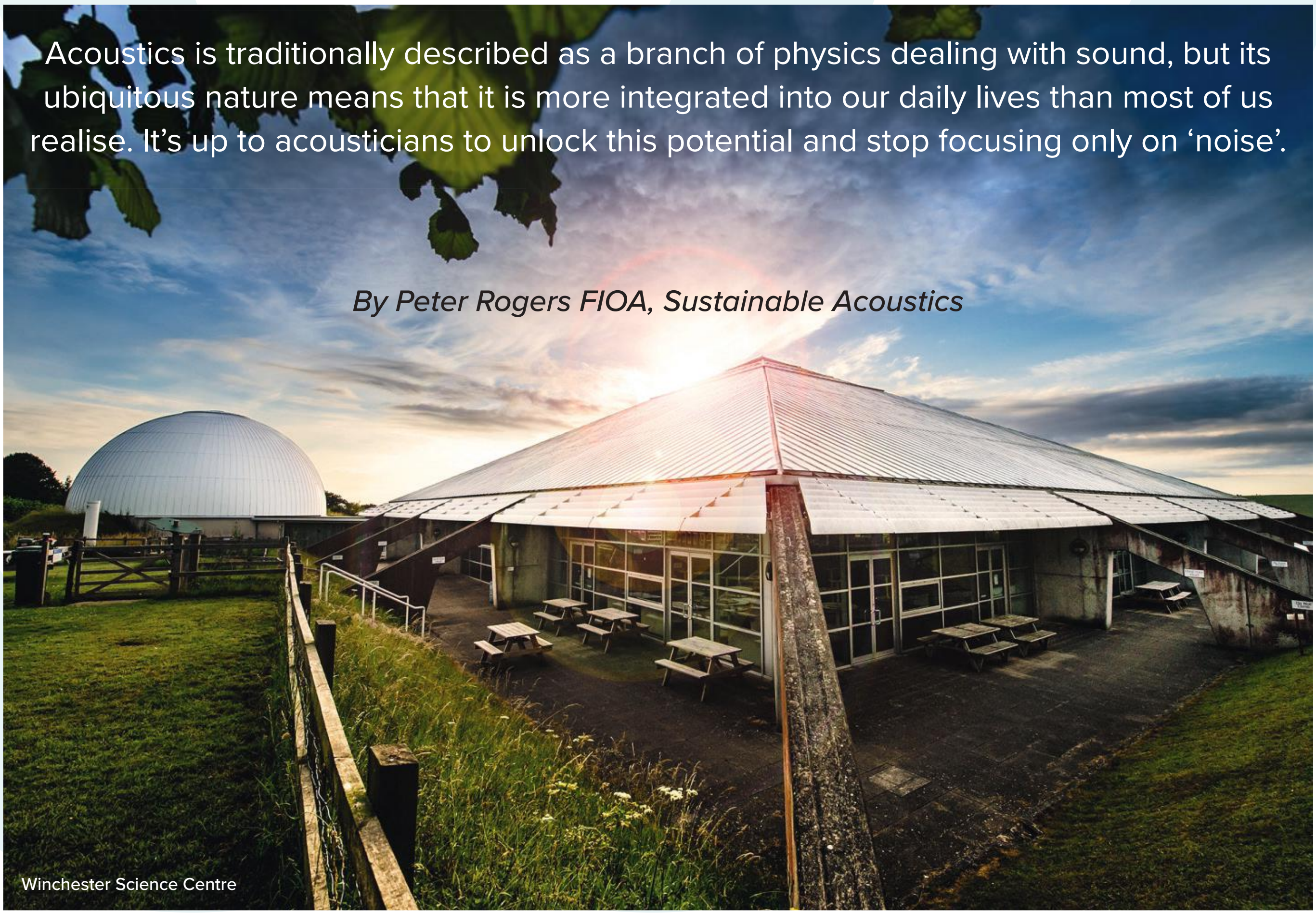
Additionally, several other environmental and sustainability accreditation schemes have been gaining traction (on UK schemes) in recent years. The most prominent of which are WELL and Fitwel. Developed over 10 years ago by Delos, now administered by The International WELL Building Institute, WELL v2 was recently piloted to enhance the existing district-scale rating system of its flagship Building Standard and set a new global benchmark for healthy buildings and communities. Fitwel was originally created by the U.S. Centers for Disease Control (CDC) and Prevention and U.S. General Services Administration in 2016, now operated by the Center for Active Design and provides tailored scorecards for existing and new buildings, to optimise design opportunities for projects to receive the Fitwel healthy building certification. On balance, WELL provides a comparatively more rigorous framework for building accreditation, where Fitwel offers a more accessible and practical route to benchmarking and space optimisation for healthy building outcomes. ◎

About the author:
Alex Krasnic BEng(Hons.) MSc. FIOA MInstSCVE
Alex is a Principal Acoustics Consultant at Vanguardia (a Buro Happold company) specialising in the acoustic design of built environment assets across the UK, Europe and Middle-East. With more than 22 years' experience, Alex has been engaged on numerous high-profile schemes requiring building acoustics expertise and he thrives on working within multi-disciplinary design teams, often led by architectural practices and where the integration of specialist noise and vibration requirements are critical to the successful delivery of a project.

Acoustics in the built and natural environment: A catalyst for equality, diversity, inclusion, and sustainability

Acoustics is traditionally described as a branch of physics dealing with sound, but its ubiquitous nature means that it is more integrated into our daily lives than most of us realise. It's up to acousticians to unlock this potential and stop focusing only on 'noise'.

By Peter Rogers FIOA, Sustainable Acoustics



Winchester Science Centre

Left:
A vibrant and inclusive community park setting, where people from all walks of life come together — requires design that helps humans and nature to thrive no matter what their diverse needs are

Where our world is designed for the eyes, it must now take account of the hearing sense, which prepares us for how well we can do in those environments. It is also true that acousticians are only now realising how much influence they can and should be having on humanity's ability to live sustainably on planet earth during the Anthropocene. (The Anthropocene Epoch is an unofficial unit of geologic time used to describe the most recent period in Earth's history when human activity started to have a significant impact on the planet's climate and ecosystems.)

The diversity in life and a growing awareness of those who are neurologically/aurally diverse[1] means that a person's response to their environment cannot be described as an 'average', but more appropriately as so called 'fuzzy data[2]'. This requires us to consider a range of possible outcomes, more akin to the quantum world, which resolves to one response in that moment and can change or adapt in the next. Such smart adaptive environments may not be that far off as Artificial Intelligence is put in control of building systems.

Imagine a vibrant and inclusive community park setting, where people from all walks of life come together to enjoy music, the sights and sounds of flora and fauna, and each other's company. Acoustics design has a significant role in creating suitable places for this to happen, whether a park, courtyard, or place inside a building, which cannot in themselves be sustainable (no matter how low their embodied carbon is) if they do not work for their intended purpose. To make these inclusive environments requires design (that includes creativity) that helps humans and nature to thrive no matter what their diverse needs are.

This article is a discussion piece which aims to bridge the gap between acoustics — a discipline that to many outside the field may see as distant and complex — and sustainability, a concept that many people are increasingly becoming familiar with as an objective, but need contextual understanding to know when that has been achieved in reality. It is also intended to help us explore how acoustics can be used in design to achieve sustainable, equitable, and inclusive solutions that foster wellbeing and environmental and natural stewardship in our built and outside environments on land, in the air or at sea.

Acoustics, equity, and inclusion

The built or natural environment plays a critical role in how people experience their surroundings and this is where acoustics comes into play; because humans need to feel safe to be able to do anything more than remain on high alert[3]. Sound is the key sense we use sub-consciously to monitor our state of safety. When an unwanted sound (noise) masks our ability to scan our surroundings, we become 'ear-blind' and this state requires us to employ cognitive resources to filter out the unwanted information, allowing us continue to detect threats.

We have not evolved away from this fundamental instinct and nor has nature. This results in stress causing physiological changes to our bodies which, if maintained, can cause poor health outcomes[4]. Those of us who struggle with neural/aural diversity need to filter out and

P42

Footnotes

1. https://auraldiversity.org/
2. https://www.igi-global.com/dictionary/fuzzy-logic-in-portfolio-selection/90982
3. Sayin (2015), 'Sound and safe' – The effect of ambient sound on the perceived safety of public spaces. https://www.sciencedirect.com/science/article/abs/pii/S0167811615000798
4. House of Lords Select Science and Technology Committee, The neglected pollutants: the effects of artificial light and noise on human health (2023). https://publications.parliament.uk/pa/ld5803/ldselect/ldsctech/232/232.pdf

manage this acoustic challenge, meaning that some of us are effectively excluded from being able to exist safely in many of our environments.

The emerging field of a soundscape approach considers the question of what conditions must be in place to support the intended use of the environment. Humans evolved to be outside and connected to nature, but now spend more than 90% of their time inside, so it is of little surprise that natural sounds can create a 'soft fascination[5]' response in humans. This means they are cognitively aroused/activated but not threatened or fighting against sound which is unhelpful, to a point where things like creativity and a sense of calm and wellness can result[6].

Above: A bustling open-plan office in which communication on telephones causes a level of noise may make it difficult to concentrate on tasks that require creativity

Indoor considerations

For example, think of a bustling open-plan office in which communication on telephones causes a level of noise which may make it difficult to concentrate on tasks that require creativity. Compare this to a quiet library or acoustically pristine national park which may be relatively free from manmade noise.

Conversely, a lively restaurant may provide a great place for social connection, but if it is too noisy it becomes an unpleasant place to be and the food taste will be affected[7]. All these experiences and how well we can tolerate them are significantly influenced by their acoustic characteristics.

If we are to foster truly inclusive spaces, we need to consider the diverse acoustic needs of different individuals likely to encounter them. Where one acoustic environment can work for the majority, this must be the obvious choice design specification for an inclusive space.

But when it will not do the job, very creative design is required in order to provide a diverse range of acoustic environments (that may be near each other) that cater for the range of people likely to use the space where they can find the place within that environment that suits their needs.

A simple example of how including all can benefit all, is to make sure that quieter spaces exist within offices with an absence of low frequency noise ingress, where people can go to concentrate or, in the case of aurally diverse colleagues, to access a space they can comfortably tolerate and achieve a state of relative calm and focus.

Designing comfortable outdoor spaces

Children, the elderly, individuals with sensory processing disorders, and people with hearing impairments are just a few examples of groups that can be acutely sensitive

Footnotes

5. Article by Popova M (2022), **https://www.themarginalian.org/2022/07/01/default-mode-network-awe-soft-fascination/**
6. **https://www.nrpa.org/parks-recreation-magazine/2013/april/the-soft-fascination-of-nature/**
7. Time magazine by Sifferlin A (2015), **https://time.com/4110938/flavor-science-explains-how-you-can-hear-the-way-your-food-tastes/**

to acoustic environments. By designing spaces with acoustics that cater to their needs, we create environments where more people feel comfortable and included. Sound-absorbing materials, strategic space planning, and careful construction methods are some of the ways acousticians contribute to creating inclusive spaces inside buildings, but the challenge is for acousticians to become creative in outside environments to develop better, more euphonic (pleasing to the ear) and healthier soundscapes that will benefit everyone.

Winchester Science Centre case study

An example is the acoustic intervention in the Winchester Science Centre, where the visitor experience was initially described as 'noisy, tiring and overwhelming'. Those visitors with additional sensory needs reported that it was almost impossible to access what the centre had to offer, so they often left the venue feeling distressed and frustrated. The acoustic intervention resulted in a change to many of the exhibits, which themselves were used to break up the space. Acoustic absorption using modular perforated blocks filled with off-cuts of sheep's wool was introduced along with the installation of suspended sound-absorbing ceiling baffles and the semi enclosure of the most sensitive learning areas, helped to provide quiet to the busiest areas. In addition a quiet space called the 'Recombobulation Room[8]' was created to provide an escape for those needing to decompress and restore themselves before exploring further.

This now means that although the main space remains vibrant and busy it is much less noisy and now has a diverse range of acoustic areas, including a place to escape and regroup. This has reportedly transformed the visitor experience, and enabled those with additional sensory needs to access the space in a way that now can be described as providing equality in terms of access.

Sustainable acoustics

A sensible starting point for creating an inclusive environment relies on getting the acoustics right for its intended use, and balances the need to keep ambient noise levels down, low frequency noise ingress under control, and an acoustic environment to be supportive of speech.

Simply designing to minimum acoustics standards will exclude many users, and is difficult to justify in terms of quality, whereas an optimised acoustic design that caters for the range of users that the environment is intended for, is what acousticians should consider to be the starting point.

Beyond inclusion, which is a part of sustainability as defined by the UN Sustainable Developments Goals, P44

Below:
Constant exposure to high levels of noise can lead to stress, and other health problems

Footnotes

8. **https://www.winchestersciencecentre.org/visiting/accessibility**

acoustics also has a role to play in delivering a sustainable future where a balance can be achieved that does not disadvantage the next generations of all species. Most would argue this is not enough and that the true goal is to use acoustics to create regenerative environments that put back more than was used to create and operate them and this approach is easier than it sounds.

Acoustics affects the construction and operation of buildings, which account for a significant portion of global carbon emissions, so considering acoustics early in the design stage can contribute to buildings that have less embodied energy, are more energy efficient and achieve more with less. Acoustics can play a role in energy efficiency by assisting the rapid deployment of the renewable energy transition (e.g. air source heat pumps, wind farms and solar farms) or providing low energy solutions that enable natural ventilation to work without overheating becoming a problem.

The materials specified by acousticians can have a large impact. By optimising the shape and number of materials and the specification of materials with good eco credentials and low embodied carbon etc. will have a large effect on projects and, by extension, will contribute to a more sustainable world.

Essential to our success as a species is for acousticians to become involved in building projects at the earliest planning stages, and use acoustics to create regenerative design outcomes with multiple benefits. One example of this is to achieve biodiversity net gain (BNG) (**https://www.gov.uk/government/collections/biodiversity-net-gain**) through our design interventions and in collaboration with other built environment disciplines — bringing nature into our buildings by specifying renewable materials, with biophilic design or with the introduction of natural sound.

In urban environments, acoustics plays a crucial role in combating noise pollution, a pervasive problem in many cities, recognised by the UN in their 2022 Frontier report[9], alongside wildfires and nature's shifting rhythms as a result of climate change. The House of Lords has recently recognised that adverse noise effects on humans have been neglected, and the Government has been asked to form an expert advisory panel to seek more consistent policy implementation across departments.

Constant exposure to high levels of noise can lead to stress, and other health problems for humans but can also be catastrophic for breeding success for birds for instance. Acousticians can work alongside urban planners to design city layouts and building orientations that minimise noise pollution, enhancing the quality of life for urban residents and contributing to healthier cities through better and healthier soundscapes.

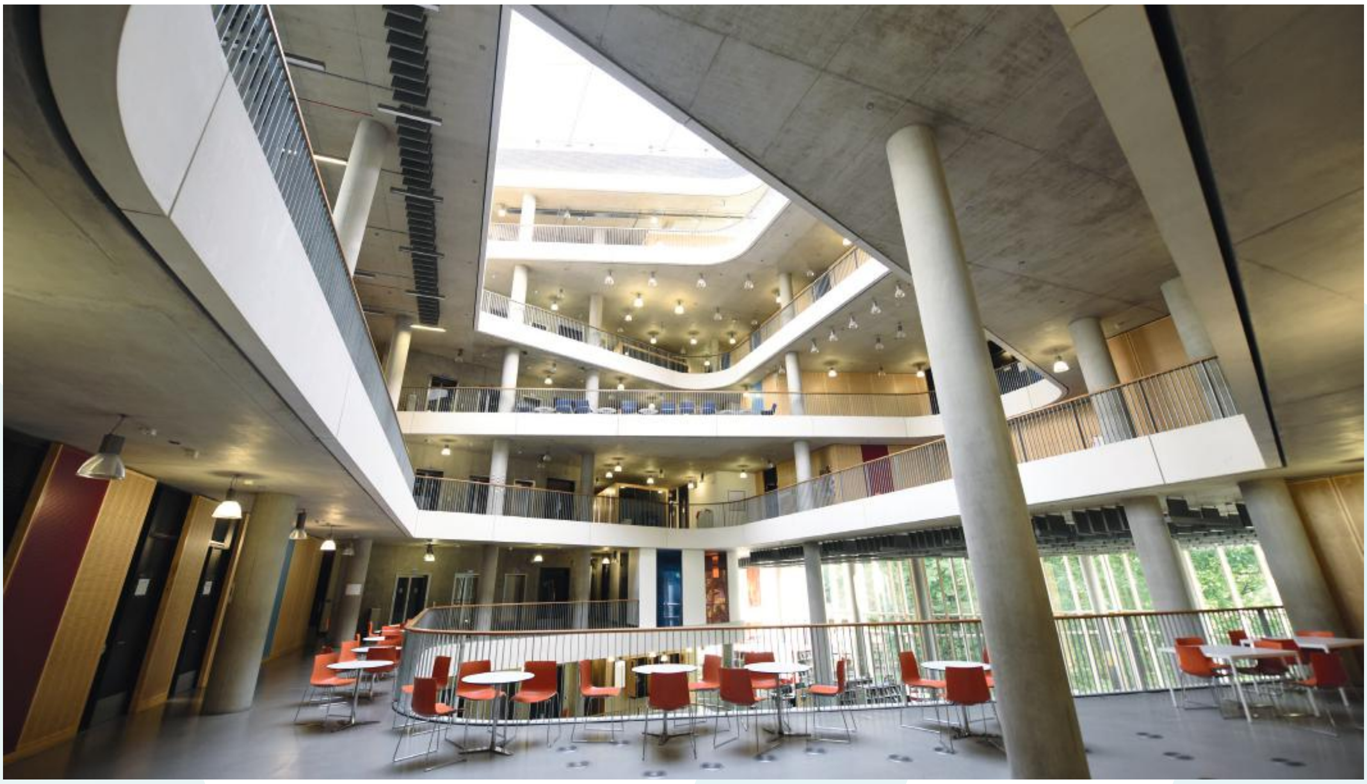
Green roofs and walls, tree belts, soft ground enhancement with certain planting, strategic placement of buildings, and traffic management or design on roads to maximise noise reduction resulting from the electrification of vehicles are just some of the methods that can be used to reduce noise levels in cities also achieve BNG. These approaches not only make cities more pleasant places to live but also contribute to urban biodiversity and can help with challenges such as reducing the urban heat island effect.

Conclusion

Acoustics plays a critical role in the built environment and external environments on land, sea and air, impacting on both sustainability and inclusivity. It's important to make the connection between acoustics and these broader societal goals to fully appreciate the profound role that sound plays in our lives, and how as acousticians we have barely begun to make our mark on the Anthropocene. As we move away from purely reducing noise to curating positive soundscapes to create a more sustainable and inclusive future, the strategic and creative application of acoustics in design is a necessity that needs to happen early in the process. Acousticians, therefore, have the opportunity and potential to be key drivers in the move towards a more sustainable, equitable, diverse and inclusive society. ◎

Footnotes

9. **https://www.unep.org/resources/frontiers-2022-noise-blazes-and-mismatches**



Acoustically comfortable spaces for teaching – a need or a treat?

The design of schools is carried out by various specialists ranging from architects and landscape designers to acoustic and fire consultants. For schools schemes in England, Wales and Scotland Building Bulletin 93 (BB93) contains detailed performance criteria for ambient noise, reverberation time, sound insulation and speech intelligibility requirements, to both make the teaching and learning spaces comfortable for teachers and pupils as well as providing a means of demonstrating compliance with Regulation 41 of the Building Regulations, Approved Document, Part:E AD:E (England, Wales) and Section 5 (Scotland).

By Dr Elena Prokofieva, Edinburgh Napier University

Left:
Gymnasiums, assembly halls, sports halls, dining areas and large atria typically have large reverberation times recorded, resulting in reduced speech intelligibility, flutter echoes, standing waves and general discomfort for staff and pupils when in use

“The acoustic consultant should collaborate closely with the end-user and design team to support the overall design process”

The design team for a school project is expected to include an acoustic consultant right from the design stage all the way to compliance testing. This article discusses some of the best practices in school classroom design, and on the advice of early involvement of acoustic specialists in the design process to avoid any future issues when the school project is completed and occupied.

Evidence collected by the UK Department of Education demonstrates that access to early education is crucial in supporting children to thrive in adulthood and contribute to society. Research has also shown that improving young children’s pre-school language skills could boost the economy by up to £1.2 billion over the course of their lifetimes[1]. Up to £180 million of government funding over the next three years will support the sector to focus on children’s development during their earliest years of life and help address existing recruitment and retention challenges. To deliver education to pupils of the future, schools must be built and maintained at the highest standard.

There are currently over 30,000 schools functioning in the UK[1]. The Office of National Statistics (ONS) showed in 2021 that the proportion of schools in ‘good’ or ‘satisfactory’ condition increased from 61.1% in April 2007 to 88.3% in April 2019. The School Estates Statistics 2019 also showed that the proportion of pupils educated in these ‘good’ or ‘satisfactory’ condition schools has hit a record of 89.6%, up from 60.8% in 2007.

The government has since approved the construction of new schools, which are are a vital part of the UK’s plan for education, as they increase choice for parents and help to drive up standards across the board. For example: the Scottish Government will contribute funding of between £220 million and £275 million in partnership with local authorities across the country to replace 26 schools, with a further phase of investment to be announced[2]. The Scottish Government has been providing sponsorship to several projects to bring together nurseries, schools — and specialist centres for pupils with additional support needs — including colleges and universities in multi-purpose campuses for pupils aged from three to 18, with additional facilities that benefit surrounding communities.

Additional requirements set by the Governmental Regulatory body for any new building, including schools, is to help with tackling the climate emergency. In Scotland’s case this is central to the new Learning Estates Strategy, with lessons learned from previous education infrastructure projects, informing future construction to create low carbon digitally enabled schools and campuses. The Scottish Futures Trust will manage the programme on behalf of the Scottish Government[2]. Sustainability acting as a key driver in the design and development of schools, as well as their management post-completion operation and maaintenance.

When a new school is proposed, its design is conducted by various specialists: from architects and landscape designers to mechanical ventilation and electrical engineers, fire, and acoustic specialists. The school is expected to be designed to provide visual satisfaction, adopt innovative technologies with pedagogy in mind and suitable for running taught activities efficiently and comfortably.

School design stages and decision-making

In Scotland, local authorities often take a leading role in the teams for new school projects, which deliver new school buildings for the public. These project teams, or ‘Hubs’, led by Council teams, include the design and construction teams, all necessary experts, and, in some cases (i.e. when a new school is replacing an existing one), representatives of the Teachers Associations.

According to Royal Institute of British Architects (RIBA), the design stages for any project include eight different stages. These stages have been compiled in collaboration with UK construction industries defined in the RIBA Plan of Work document[3] and identified as follows:

- Stage 0: strategic definition
- Stage 1: preparation and briefing
- Stage 2: concept design
- Stage 3: spatial coordination
- Stage 4: technical design
- Stage 5: manufacturing and construction
- Stage 6: handover
- Stage 7: use.

At the concept design stage (RIBA Stage 2 as above), the key decisions are taken regarding the scheme location, topographical orientation, allocation of spaces for external teaching, playgrounds and sports pitches (including Multi Use Games Areas (MUGAs). At this stage the main input from the acoustic designer is to investigate the prevailing noise environment affecting the proposed location and to inform the strategy for the ventilation of the school building(s), such as passive (e.g. openable windows) or mechanical ventilation, as well as the suitability of the proposed locations for outdoor learning spaces, and to assess the effect of noise P48

Footnotes

1. Department for Education. Press Release (2022)
2. New schools and campuses for Scotland (published on **www.gov.scot**)
3. RIBA Plan of Work 2020 Overview. Published by RIBA **(www.ribaplanofwork.com)**

associated with school activities on the nearest noise-sensitive locations (e.g. residential properties).

At this stage there is some design flexibility to relocate the building(s) and associated facilities, propose fences or acoustic barriers following an assessment of surveyed environmental noise levels.

At the technical design stage (RIBA Stage 4), internal acoustics are considered in greater detail. The internal school layout is proposed, and the types of constructions for the entire project are assessed and specified. Design features, such as teaching spaces, whether open plan or enclosed types of classrooms, dimensions and locations of large spaces (e.g. sports halls, canteens, atria, assembly halls, libraries, etc) are also determined. In addition to the teaching and learning spaces, the administration and ancillary places are also allocated in the most efficient way to complement the acoustic design. At this stage the internal design can still be changed to create the best possible environment for teaching and learning. This means that the acoustic consultant should work closely with the end-user and design team to oversee that the scheme design is checked and verified before being approved by the client. Once the construction types and main design features are agreed with the team and the design is approved, only minimal changes may be accepted, and the acoustic design must now coordinate within the design framework.

Below: Acoustic comfort is not a luxury, but rather a very important part of the pedagogy process

At construction stage (RIBA Stage 5) the design changes are already limited, however the participation of the acoustic consultant in the project becomes even more important. The acoustician should be able to visit the site regularly and monitor the construction processes and to advise on acoustic-related issues during the build. Visual inspections and sample acoustic testings of the rooms are scheduled to confirm early compliance or to raise the awareness of potential performance-related issues.

Design guidance on school acoustics

The key guidance document pertaining to the acoustic design of educational buildings is Building Bulletin: BB93, updated in February 2015[4] (providing the means to demonstrate compliance with the AD:E and Section 5) with additional design guidance provided in *'Acoustics of Schools — a design guide November 2015'* published by The Association of Noise Consultants (ANC)[5]. These two documents cover all aspects of acoustic design relative to primary and secondary schools but can, in some instances, also be used to inform the acoustic design of other education establishments (e.g. nurseries, colleges and universities).

The acoustical design approach for a new or refurbished school building is to review and provide advice on the key aspects related to sound generation within (due to both internal and external sources) and, generation outside of the building, to include:

- control of external noise breaking in to the school building;
- control of the noise breaking out from the school (including plant noise) affecting the nearest noise-sensitive properties);
- control of noise and vibration generated within the school building from building services by both airborne and duct-borne means;
- sound insulation between teaching spaces and non-teaching areas; and
- control of reverberation times in key areas.

Footnotes

4. Acoustic design of schools: performance standards. Building Bulletin 93. Department for Education (updated February, 2015)
5. Acoustics of Schools - a design guide. Published jointly by the Institute of Acoustics (IOA) and the Association of Noise Consultants (ANC). November 2015, ANC

The first two aspects are associated with the school as a whole, and are therefore covered by the initial design team at RIBA Stage 2. All others are usually considered later in the technical design (Stage 4).

BB93 specifies appropriate internal ambient and building services noise levels (including for any concessions for natural ventilation) for teaching and non-teaching areas, as well as categorising the noise activity (as a 'source' room) and the noise tolerance (as a 'receiving' room) to inform the airbourne sound insulation requirements between spaces and reverberation time criteria.

Excerpts from the Tables 1 and 6 (BB93) are shown below.

Below: Table 1 Noise activity and sensitivity levels ans upper limits for indoor noise level

Bottom: Table 6 Performance standards for reverberation time

The ventilation noise levels are discussed in BB93 with relation to the ambient indoor noise levels (in terms of $L_{Aeq,30\text{-}mins}$), but not defined in terms of Noise Rating (NR) curves. It also should be noted that the ventilation rates, thermal comfort, and indoor air quality are covered by a separate document, Building Bulletin: BB101[6].

Examples of effect design aspects on acoustics

It is expected that the design process should be done with pedagogial requirements in mind, meaning that the main purpose of the building is for teachers to work in a comfortable environment and to optimise learning outcomes for pupils. From extensive personal P50

Type of room	Room classification for the purpose of airborne sound insulation in Tables 3a and 3b		Upper limit for the indoor ambient noise level $L_{Aeq,30mins}$db	
	Activity noise (Source room)	Noise tolerance (Receiving room)	New build	Refurbishment
Nursery school rooms *Primary school*: classroom, class base, general teaching area, small group room *Secondary school*: classroom, general teaching area, seminar room, tutorial room, language laboratory	Average	Medium	35	40
Open plan: (See also section 1.8) Teaching area Resource/breakout area	Average	Medium	40	45

Type of room	T_{mf} seconds	
	New build	Refurbishment
Nursery school rooms *Primary school*: classroom, class base, general teaching area, small group room SEN calming room:	≤ 0.6	≤ 0.8
Secondary school: classroom, general teaching area, seminar room, tutorial room, language laboratory Study room (individual study, withdrawal, remedial work, teacher preparation) Science laboratory Design and technology: Resistant materials, CADCAM area, Electronics/control, textiles, food, graphics, design/resource area, ICT room, art	≤ 0.8	≤ 1.0
Open plan: Teaching area	≤ 0.5 (section 1.8)	≤ 0.5 (see section 1.8)

Footnotes

6. Guidelines on ventilation, thermal comfort and indoor air quality in schools. Building Bulletin 101. Version 1. August 2018

experience of participation in school design projects, it can be noted that the chosen room layout and the allocation of teaching and non-teaching spaces within the school building can harbour either a positive or negative influence on the acoustic performance of individual spaces. Some examples are discussed below.

Privacy issues

The level of activity noise and expected tolerance of noise are outlined in BB93 for all spaces, and are used to inform appropriate sound insulation criteria for the separating partitions. However, privacy requirements are only discussed in terms of minimising speech intelligibility and considered only as during the teaching activities, i.e., when sufficient speech privacy between teaching groups is requested (e.g. in open-plan classrooms) in order to avoid distraction (i.e. in Footnote 5).

Acoustic privacy for interview and consulting rooms, quiet rooms, and rooms for teaching pupils with special needs is not discussed in any of the guidance documents. Furthermore, partitions between store rooms adjacent to noise-sensitive rooms can be classified as non-acoustic (e.g. using these as buffer zones between noiser-sensitive rooms). This can be considered as a good design practice in areas where noise-sensitive rooms are not associated with personal information spoken out loud (such as music rooms or design and technology laboratories or workshops), but should not be considered acceptable in privacy-sensitive locations.

Open plan classrooms vs enclosed classrooms

Open plan classrooms are especially popular in the design of both primary and secondary schools. The flexibility between the spaces and ability to increase the inclusivity for all groups of pupils are key in selecting this type of room design. There are three main types of open plan classrooms (i.e. as shown in Footnote 5):

- fully open;
- semi-open; and
- flexible open classrooms.

The **fully open** classroom design provides a large degree of flexibility of the space use with divisions provided only by means of loose fixtures (moveable screens, bookshelves, coat hangers, etc).

Semi-open classrooms are defined by the walls with openings in them (i.e. to circulation spaces).

The **flexible** classrooms have installed moveable partitions which allow the room configuration to change from fully enclosed to fully open.

It has been noted from project experience that often these types of classrooms can create disruption to teaching activities (i.e. lack of privacy in conversations, noisy activities next to quiet studies, etc) and may not be suitable for all school pupils or teaching methods.

The table below shows the measurements of the ambient noise and reverberation time in two primary school classrooms with semi-open layout and then after remediation works conducted to enclose the room and the comparison with BB93 requirements.

The results suggest that creating a physical separation between the corridor and the classroom affected the ambient noise levels and the reverberation time, although it also shows that further improvements may be required to be able to use this classroom to comply with BB93 for standard teaching spaces.

Pupils with special health and education needs issues

People with special educational needs and disabilities (SEND), behavioural or health-related challenges (both

Location	Measured RT, T_{mf}, sec	RT, $T_{mf,\,max}$ as per BB93	Measured ambient noise level, L_{Aeq}, dB	Ambient noise level, as per BB93
Semi-open plan classrooms	1.29 1.05	≤0.5 (open plan classroom)	40 38	≤40 (open plan classroom)
Same classrooms, enclosed	0.79 (with extra panels added) 0.92 (without extra panels added)	≤0.8 (classroom with door)	34 25	≤35 (classroom with door)

teachers and pupils) may find open plan classrooms extremely difficult to work and study in. Concerns and complaints are regularly raised about their suitability for primary or secondary schools. Studies[7,8] have been conducted on the impact of high levels of reverberation and background noise on autistic or hearing-impaired school occupants.

In BB93 stricter requirements are applied to ambient noise levels, sound insulation and reverberation times for the classrooms intended for teaching pupils with special hearing and/or behavioural needs. These requirements exclude any use of open plan or semi-open plan classrooms, and sometimes do not permit the use of open window ventilation, neccessitating mechanical ventilation to be used instead.

In addition to discomfort due to activity-generated noise within classrooms, ventilation and thermal comfort issues could result in unsuitable learning environments for pupils occupying school buildings[9] and should be addressed as early as possible. With the inclusion of mechanical ventilation into the building design, ambient noise levels may be unduly affected (when mechanical systems are operational), which can create incompatibility between requirements set out in BB93[4] and BB101[6].

Large halls reverberance

The large halls, such as gymnasia, assembly halls, sports halls, canteens and large atria can typically exhibit long reverberation times, therefore resulting in poor speech intelligibility and a prevalence of flutter echoes, standing waves and general discomfort for staff and pupils when in use. These areas are likely to be double height and have hard floor and wall coverings (for health and safety reasons), with absorption only provided under the roof and with acoustic panels installed along available wall spaces. The acoustic treatments which are recommended may include 'Class A or B' absorptive panels, or 'Class C' perforated plasterboard (as defined in ISO 11654:1997). The main challenges that arise at this stage, are to find the best combination of the absorption parameters, aesthetics, and the cost of treatments to satisfy both the requirements of the BB93 and the project budget. Various options can be considered, but the specification of treatments may take longer due to an inability to trial them prioor to an architectural decision. A simple room acoustic calculation or software modelling exercise may be provided by the acoustic consultant at the design stage to sinform this decision.

Similar issues may also affect the acoustics of ordinary classrooms, when consideration is only due to the aesthetics e.g. where hard surface finishes are specified for walls, floors and ceilings (such as cross-laminated timber constructions, exposed concrete ceilings, etc). More often than not, the addition of acoustic treatments are required to meet the stipulated reverberation time targets.

Conclusions

As the above examples suggest, early decisions influencing the acoustic design have to be made before the technical design stage, acknowledging that doing so affects the wider approach to the scheme design. While the project team might not include acousticians at the scheme onset, and are therefore not in grade to highlight expected acoustic performance-related issues at the early design stage. Additionally, for many projects budgetary constraints may preclude any computer modelling typically used to simulate the acoustic performance of teaching spaces and the evaluation of all design options prior to eventual specification.

If the acoustics issues are not addressed at the design stage with the input of an acoustician, the completed building may (at best) result in uncomfortable spaces for both work and studying and (at worst) lead to non-compliances in regulatory requirements.

Acoustic comfort should not be considered a luxury, but rather a very important part of the pedagogy process, such that any design or construction shortcomings may result in end-user complaints, resulting in investigative and remedial works at the post-completion stage, which are likely to bear undesirable costs both financially and in terms of disruptive works.

Author's acknowledgements
I would like to thank my colleagues at Robin Mackenzie Partnership, Edinburgh Napier University for providing the site testing data and invaluable advice for this work.

Footnotes

4. Acoustic design of schools: performance standards. Building Bulletin 93. Department for Education (updated February, 2015)
6. Guidelines on ventilation, thermal comfort and indoor air quality in schools. Building Bulletin 101. Version 1. August 2018
7. F. Caldas, B. Masiero, L. M. Wang. How Classroom Acoustic Conditions May Impact Autistic Students: A Review. Internoise 2022. Conference Proceedings
8. E. Greenland. Classroom acoustics design beyond BB93 - refurbishment of a hearing-impaired unit in a mainstream primary school. Internoise 2022. Conference Proceedings.
9. L. M. Wang. Relationships between acoustics, thermal, indoor air quality, and lighting conditions on student achievement in K-12 classrooms. Internoise 2022. Conference Proceedings

Acoustic isolation for Sadler's Wells

Case study: A bespoke engineering for a special project.

By Adam Fox, Adam Fox, CEng, MIMechE, AMIOA, Director at Mason UK Ltd

Above:
A section of the steelwork destined for the main dance studio being lowered into place

The East Bank development is an ambitious project that is part of the London 2012 legacy. This development includes a new site for Sadler's Wells, the world-renowned dance theatre. Bringing the vision for the new building to life has involved significant engineering, including ensuring that the building's occupants wouldn't be disturbed by noise and vibration made by freight trains passing nearby. To help overcome this, vibration control specialist Mason UK designed and manufactured a system of bespoke bearings to isolate against sources of vibration.

A unique collaboration

The East Bank development, located on the east bank of the River Lea in Stratford, is part of the Queen Elizabeth Olympic Park. Once completed, it is estimated that the new cultural quarter will bring an additional 1.5 million visitors to the park every year, create more than 2,500 new jobs and generate an additional £1.5 billion for the local economy.

The East Bank is described as a 'new powerhouse for innovation, creativity and learning' and its name deliberately invites comparisons with South Bank in central London. The development brings together universities and world-famous cultural institutions, including University College London, UAL's London College of Fashion, the BBC, Sadler's Wells and V&A East.

The Sadler's Wells Theatre is in Clerkenwell, and the site has been continuously occupied since the time of the Restoration in the late 1600s. The East Bank will be home to Sadler's Wells East, an entirely new site, offering a 550-seat dance theatre, a new choreographic school, and a hip hop theatre academy.

The building was designed and created by architects O'Donnell and Tuomey, and dance practitioners were consulted in the early phase of the design process to ensure the finished building caters to their needs. However, for the building to function as intended, sophisticated acoustic engineering was required. Having consulted with specialist acoustic consultant Charcoal Blue and structural engineer Buro Happold, the contractor Kilnbridge turned to vibration control specialist Mason UK.

The major challenge seemingly facing the scheme was the proximity of the site to a major trainline, including the Elizabeth Line which opened in May 2022. With freight trains passing right across the front of the site, there would typically be plenty of low frequency vibration generated, manifesting as low frequency noise (akin to 'bass' or rumble) in the dance studios without correct treatment. This would have significantly affected the performers and spectators.

However, a vibration monitoring survey was undertaken at the project site in 2016 and it concluded that re-radiated **structure-borne** noise from train movements in the proximity of the building would not be a problem for the project.

Vangelis Koufoudakis from Charcoal Blue said: "The biggest challenge was the number of low-background mechanical plant noise in spaces designed for dancing within the confined footprint of the building; that was the primary reason behind a requirement for the isolated constructions, acoustic isolation zones and jacked-up floors."

Studio One

Mason UK was working on several studios within the building that required acoustic isolation, but the biggest challenge came from Studio One. While all the dance studios in the facility are large, Studio One is a 200-capacity dance studio constructed on a steel frame which sits on top of the 550-capacity dance theatre. To support such a large studio, five main trusses spanning 35 metres and weighing 20 tonnes each had to be installed.

To prevent vibration and low frequency sound from being transferred between sensitive spaces, the Studio One structure had to be decoupled from the dance studio structure which required a bespoke solution. Acoustic floating floors (where the top of the floor sits on resilient elements such as springs or rubber are often the most effective solution for isolating dance studios. Indeed, Mason installed several floating floors for Kilnbridge, the contractor for Sadler's Wells East. However, due to the size and mass required for Studio One, rubber bearings supporting the perimeter were a better option, used to isolate the vast steel trusses from the concrete structure.

A bespoke solution

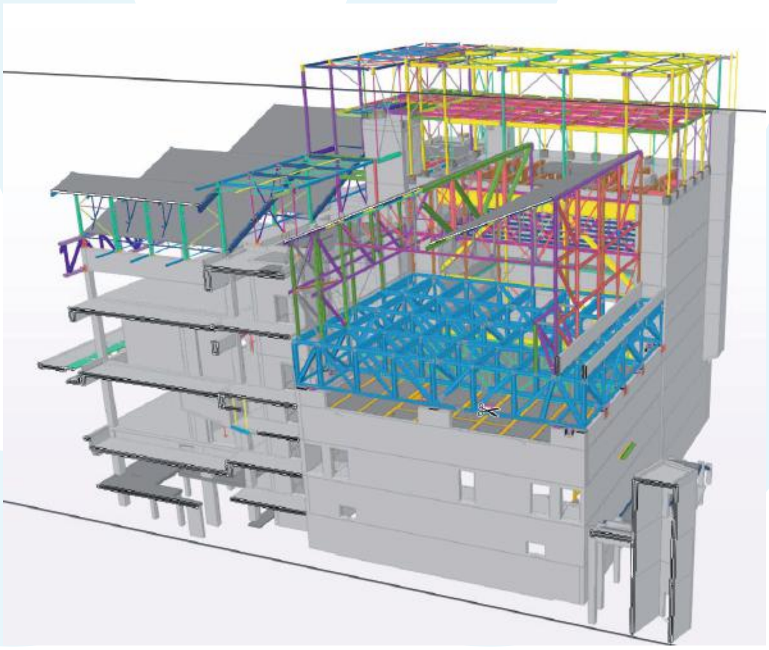
With an area this size, it made more sense to position point loads of large bearings spread out around the perimeter. In total, 11 locations were required to support the trusses at intersections. Having lots of isolators spread out over a floor this size, as would be the case with a floating floor, would be less cost effective and the use of large bearings also had the benefit of keeping contact points to a minimum — offering superior acoustic performance.

Rubber bearings can be designed to provide low natural frequencies, as low as 4 to 5 Hertz if necessary. The low dynamic stiffness of Mason proprietary rubber formula makes it a highly effective material choice for an isolator, even for the low frequency vibrations that would be generated by group dance activity. The kind of bearings used for Sadler's Wells East were the type usually used when isolating entire buildings. Furthermore, as this is not an off-the-shelf product, each bearing had to be specifically designed to handle the loads it would face.

Mason worked closely with the structural engineer to achieve this engineering solution and it was necessary to determine the load that each bearing would be subjected to. From the perspective of the structural engineer, load conditions including very significant emergency conditions had to be supported, but a bearing based on a load requirement that is much higher than what will be typically experienced would not compress enough and therefore fail to deliver the required acoustic performance.

In addition to designing bearings that would respond in the right way to the true loads they would be subject to, it was also necessary to take into consideration P54

Below:
The complex internal framework for the main studio, Flytower and other plant areas were isolated on natural rubber bearings



how they would work around the existing building structure. For instance, in some places there would not be sufficient width of wall to accommodate a large bearing, so two or three smaller ones had to be used instead. Being able to adapt to different space envelopes was another advantage of using bespoke bearings.

Above: Inserting the floating floor springs before commencing jacking, to within 5mm across the whole area

Bespoke shear keys

Although the bearings provide the ideal acoustic solution, they also introduced a further engineering challenge — handling lateral forces. Structural engineers need to ensure the building is designed to withstand the impact of lateral forces, such as wind loads from hurricanes or even terrorist activity. In the case of Sadler's Wells, significant collapse forces had to be supported.

Mason UK therefore had to design a system of bespoke shear keys to accompany the bearings. Because the forces were so large, Mason UK proposed separating into

- 'working' day-to-day forces to be handled with acoustic bearings placed laterally; and
- 'emergency' load conditions for which large steel bump stops were incorporated.

This approach greatly reduced cost and prevented the need for bearings which for day-to-day forces would be far too stiff.

Acoustic bearings were also used to isolate the entire plant area at roof level – unique steel to steel connections were developed as a simple way to reduce uncertainty of noise and vibration generated by air handling and water heating systems.

The other studios

Although the work on Studio One was the most challenging, it was far from being Mason's only contribution to this building. In total, they also designed and supplied seven concrete sprung floating floors for different studios spread across two levels. Floating floors provide a gap or clearance between the floor and the underlying structure, providing isolation against vibration transfer as well as and airborne noise from adjacent studios.

Concrete floating floors can be supported on elastomeric elements or springs. The latter have far less internal damping than rubber so can absorb more vibration.

The jack-up floating floor, pioneered by Mason Industries in the 1960s, remains the most effective construction method for installing a floating floor. This uses the Mason jack-up system to raise a concrete layer using adjustable jacks. More specifically, helical springs provide support to the concrete floor, absorbing any positive sources of vibration. The system offers a high level of flexibility and guarantees an air gap.

A legacy to be proud of

Once completed, Sadler's Wells East will stand out as one of the world's most innovative dance studios and a shining example of the London 2012 legacy. All of those involved in the project have shared a sense of pride in helping deliver on this ambitious vision.

"It always exciting to be involved in projects of this scale and the unique challenges they present," said George Taylor, a senior project engineer with Mason UK. Marius Butnaru, a site engineer with contractor Kilnbridge, was equally excited about his involvement in this project. "These are highly specialised structures, so it is a privilege to be involved in a project like this."

Discussing the unique challenges of this project, George explained that "it was clear that for these large steel trusses, we needed to design a bespoke solution, including specially designed shear keys. This was similar to structural work, so we had to work closely with the structural engineer to get the design perfect, both from a structural point of view, but also from an acoustics point of view."

Below: Isolated column supports at rooftop level. A nerve-wracking inspection!

What constitutes a sustainable acoustic material?

Environmental concerns are triggering the need for energy-efficient buildings, boosting the demand for sustainable building construction materials.

By Barry Jobling MSc, BSc (Hons), MIOA and Neha Sharma, acoustics engineer at Hoare Lea

Traditional timber or rare natural wood sourced by unsustainable logging practices, causes deforestation and habitat destruction

Acoustic materials play a crucial role in not only ensuring optimal acoustic performance in buildings but equally influencing occupant comfort, productivity, and overall wellbeing. The access to reliable information on such acoustic materials, which not only meets acoustic performance requirements but also aligns with environmental and economic sustainability goals, has thrown open a challenge for acousticians and design teams.

While on one hand, manufacturers are producing novel acoustic material solutions with reduced environmental impacts, on the other, the availability of comprehensive data on the acoustic characterisation and sustainable data, such as their lifecycle costs and embodied carbon emissions, remains limited. This article aims to highlight the need to equip acousticians to adequately provide architects, engineers, and construction professionals with valuable information on acoustic materials, and enable them to make informed decisions during the design and specification process on acoustic and environmental fronts.

Sustainable constituents of acoustic materials

Acousticians have the potential to positively influence sustainable design and development in a variety of ways. Practitioners contribute to specifying many materials in buildings, and wider infrastructure projects, which presents an opportunity to affect the adoption of both good acoustic and sustainable materials. However, for acoustic designers to feel able and empowered to promote and specify better, more environmentally-friendly solutions, they require reliable and comparable information that can constitute valued sustainable credentials.

Though there is a plethora of sustainable acoustic product alternatives being developed and commercially marketed, the real challenge lies in the awareness of validated information that can aid in making informed choices to present to clients. Within the acoustic fraternity, there is ample knowledge of how to articulate, suggest, and develop acoustic materials, however there are limitations, when it comes to understanding the applicable sustainability standards for material selection. Nevertheless, when striving for sustainability, it is advantageous to start with the basic principles.

In 1987, the United Nations Brundtland Commission, in their report, *Our Common Future*, defined sustainability as '*meeting the needs of the present without compromising the ability of future generations to meet their own needs.*' A material is said to be sustainable when it is produced, used, and disposed of in a manner that is least detrimental to the environment, promotes social responsibility, and ensures economic viability. These products are energy-efficient, emit fewer greenhouse gases, and are non-toxic, ensuring the wellbeing of the environment and people. Moreover, sustainable materials are durable and designed to fit into a circular economy model, where they can be reused, remanufactured, or recycled, contributing to a more responsible and efficient consumption pattern. Often such materials are defined by a life-cycle assessment, but some materials will major on specific sustainability factors such as:

- low carbon;
- recycled content;
- re-use potential;
- recyclability;
- limitation of volatile organic compounds; or
- absence of restricted substances.

Material assessment techniques

The Life Cycle Assessment (LCA) tool is one of the most popular and widely used conceptual frameworks for the assessment of sustainable materials, used to evaluate the environmental impacts of materials throughout their typical lifecycle, from extraction to disposal. While assessing materials for various targets, LCA plays a crucial role in determining the most environmentally-friendly options. Sustainable acoustic materials are designed to minimise their carbon footprint and ecological impact while providing effective sound insulation or absorption. LCA helps to identify such materials by analysing factors like raw material sourcing, manufacturing processes, transportation, usage, and end-of-life scenarios, that promote acoustic comfort without compromising the planet's wellbeing.

Being an invaluable resource for sustainability evaluation of a material use, the LCA tool, focuses solely on sustainability aspects and may not encompass acoustic considerations. Though, LCA enables informed decision-making to enhance environmental performance, specialised tools or assessments are required additionally to address acoustic aspects and their impact on the surrounding environment and communities. Combining LCA with other tools tailored to assess acoustic factors will lead to a more holistic approach to evaluate products and processes. Accessing such integrated LCA tools will enable acousticians to identify potential trade-offs between acoustic performance and sustainability criteria, thereby recommending optimised choice of materials. P58

Above:
Acousticians should aspire to provide architects, engineers, and construction professionals with valuable information on acoustic materials, and enable them to make informed decisions during the design and specification process on acoustic and environmental fronts

Selection of sustainable acoustic materials

Acoustics has an indispensable role in the sustainable design of buildings, seamlessly blending environmental consciousness with human-centric spaces. Acoustic principles are often incorporated into architectural and space planning, for instance, optimisation of energy efficiency through sound-absorbing materials and, reduction of the need for excessive heating or cooling by strategic ventilation design layouts. Moreover, mindful acoustic design fosters healthier indoor environments by minimising noise pollution and enhancing occupant comfort and wellbeing.

Some of the currently used acoustic materials in the construction industry may not be sustainable. Striking examples include insulating materials such as particular foams and mineral wools, that are synthetically developed, thus contributing to greenhouse gas emissions during their production. Additionally, traditional timber or rare natural wood sourced by unsustainable logging practices, causes deforestation and habitat destruction. Petroleum-based plastics used in insulation and lagging are not environmentally-friendly, as they take hundreds of years to decompose, leading to pollution and waste generation.

These examples represent only a small selection of the numerous acoustic material solutions that currently lack sustainable credentials.

Recent years have seen the emergence of innovative alternative noise control materials:

- traditional foam, mineral wool, and timber products are being replaced by their eco-friendly and high-performance alternatives, often locally sourced from nature, made from renewable resources or recycled materials;
- recycled rubber products, derived from discarded tyres, are effective in reducing impact noise in flooring applications;
- sustainable biomaterials such as mycelium-based composites, offer great potential in absorbing and diffusing sound waves; and
- smart structural developments have led to the creation of acoustic metamaterials, which exhibit exceptional sound-absorbing properties at targeted frequencies, making them ideal candidates for noise control in various industries, which could replace the need to provide alternative control measures.

These promising alternative materials enhance noise reduction capabilities and reflect a growing commitment to environmentally conscious practices in designing sustainable buildings.

Finally, it is essential to consider the crucial factors beyond acoustics and sustainability, including resistance to fire, durability, hygroscopicity (the tendency of a solid substance to absorb moisture from the surrounding atmosphere), to be vermin-proof, rot-proof and protected against bacteriological growth.

All these factors ensure the safety, longevity, and overall quality of the building. Overlooking them can lead to potential hazards and costly maintenance issues. A universal approach to material selection that encompasses these elements is essential for creating resilient, safe, and enduring structures that provide a healthy living and working environment for occupants.

Call to action!

With a broad range of parameters and a wide choice of alternative materials at our disposal, it is imperative to shortlist the sustainable acoustic material in a way that can lead to informed decisions and influence our approach to specification. The intent all along has been to inspire acousticians to keep up with the ever-growing need to make sustainable choices for acoustic materials, and being mindful of the various other purposes a material may serve.

Academicians, researchers, and industry experts should collaborate and effectively apply their capabilities to promote the application of sustainable acoustic materials, with the aim to evolve guidance and develop a reference database as an industry-shared resource to have greatest impact, accelerating adoption of more sustainable materials in acoustic design.

About the author:
Neha Sharma MSc (Res), BE (Mech), AMIOA,
is an acoustic engineer at Hoare Lea, London. She also has more than five years of research experience in acoustic products engineering, where she has applied her expertise to diverse projects for acoustic product development and environmental noise control solutions. Neha has recently completed her PhD in acoustics engineering where she has been exploring the acoustic capability of materials, thereby contributing towards sustainable acoustics innovation. Alongside her professional role, Neha is also a passionate STEM ambassador.

About the author:
Barry Jobling MSc, BSc (Hons), MIOA,
is the Acoustics Group Director at Hoare Lea with more than 20 years of experience. Since moving from environmental engineering to acoustics, Barry has accumulated extensive experience in diverse sectors and building types. Barry is also called upon for expert advice, involving in-depth investigation and working with legal professionals. He is also actively involved in industry improvements such as speaking at conferences, contributing to publications, sitting on standard committees, and being part of cross-discipline working groups.

Growing pains

Alec Korchev explores the phenomenon of the creaking noise in tall buildings (and sets our minds at rest).

By Alec Korchev

About 78% of all the world's current supertall and megatall buildings will have been completed between 2010 and 2024. Many more are being planned, proposed, or are already under construction. With such a rapid development in construction technology, it is unsurprising that certain growing pains can emerge. These can include (among others) complications with lifts, water distribution systems, resonances in the façade systems and, of course, wind-induced creaking.

In the UK, we only have one supertall building (The Shard at 309.6 metres) but we have a number of tall buildings under 300m in height that are going up at a similar rate and facing the same challenges. Creaking noise specifically being a notable concern for residential buildings and those containing rooms for residential purposes (e.g. hotels).

These creaking events are triggered by a combination of conditions. Often brought on by high wind speeds, the effects can be amplified when high winds pass through built-up areas, directing wind energy towards tall buildings along their path, and affecting the local micro-climate.

Below:
Tall buildings are designed to move and bend in high wind conditions

A supertall building is one that is 300 metres (984 feet) or taller.
A megatall building is a nerve-shattering building that is 600 metres (1,968 feet) or more.

The noise

A single creak often lasts between one to two seconds with a regularity that ranges from rarely observable to about every second resulting in asynchronous cacophony. Noise levels due to creaking are also variable, ranging from barely observable above background right up to the potential to disrupt sleep.

Residents tend to describe the sound as “concerning”, “disconcerting”, or even “worrying”. It is not a sound they expect to hear, and the assumption is that there must be something wrong with the building. Although, presumably without first-hand comparative experience, some have described the creaks as comparable to a 17th century pirate galleon straining against a storm.

There is no published guidance on the assessment of creaking noise, however a range of anecdotal experience can be used to inform how it might be approached. The emerging consensus is that the level of noise alone is not sufficient to quantify the phenomenon and assess its likelihood to cause adverse effect, but rather, the regularity of events should also be considered.

The mechanism

Tall buildings are designed to move and bend in high wind conditions, owing predominantly to two factors:

1. the force of the wind on the face of the building causes a ‘bending’ of the structure in the direction of the wind; and
2. vortices being shed around the building, forcing the building to sway in the dynamic wind flow of the surrounding micro-climate.

This deflection is understood to be intentional and structurally safe.

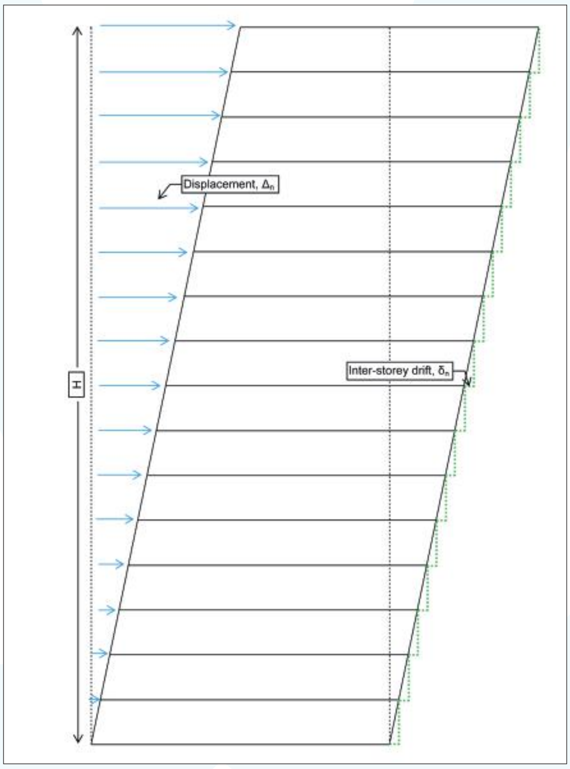
As a building flexes and bends, a lateral deflection occurs between adjacent floor slabs, relative to one another (referred to as inter-storey drift). This deflection puts a strain on internal structures within the building, which are forced to move slightly against one another and the resultant force needs to overcome the static friction (or ‘stiction’) inherent in connections between the elements.

The emerging explanation for the creaking sound is that each slight movement in which the wind-induced force overcomes the static friction, this generates an individual ‘tick’ sound, and that a sequence of these sounds occurring in succession generates the ‘creak’ which has been reported.

Ongoing research

Due to the discretion required on many of these developments, information regarding the study of this issue is scarcely published or openly discussed. In the autumn of 2022 I began a PhD research project to study the matter more comprehensively, with a view to developing a risk assessment protocol to predict at the design stage which buildings could creak, in order to implement systems to control the effect, as well as to explore sustainable retro-fit solutions to mitigate the noise in already creaking buildings. This research will include collaboration with other acousticians involved in this matter, developers, and building materials and system suppliers. I am currently looking to identify recently built tall buildings that don’t creak, to study what differences in these builds might have protected them from the phenomenon.

The project is supported by The Association of Noise Consultants and Clarke Saunders Associates. For more information please visit **www.clarkesaunders.com** or contact me at **akorchev@clarkesaunders.com** directly.



Left: General relationship between building displacement and inter-storey drift

Above:
It is often beneficial to include acoustically absorptive finishes in spaces used for speech, such as offices and teaching spaces

What is reverberation?

Have you ever noticed how sound behaves differently in large spaces with hard surfaces (for example museums, atria) versus how it behaves in smaller spaces with soft surfaces (for example bedrooms)? Or how large spaces sound more ‘echoey’ than smaller spaces? That’s reverberation!

By Nigel Burton, Director of Acoustics at Temple

Often shortened to ‘reverb’, this is the persistence of sound in an enclosed space. When sound waves are produced, they travel through the air until they encounter an object, which can reflect or absorb them. In a room or other enclosed space, the sound waves bounce off the walls, ceiling and floor, creating a series of reflections that can continue for several seconds. These reflections can create a sense of space and depth in the sound, giving it a sense of ‘ambience’ or ‘room sound’. Reverberation is an important aspect of acoustic design and is used in many musical and audio production contexts, such as in music venues, recording studios, and even in virtual reality and gaming applications, to create a more immersive experience.

What affects reverberation?

The level of reverberation in a space depends on several factors including:

- the size and shape of the room;
- the materials used in its construction; and
- the placement of objects within the space.

Different types of reverberation, such as short or long decay times, can be achieved by using different materials or by placing sound-absorbing materials in certain areas of the room.

The ideal reverberation time

This all depends on what the space is being designed for. This said, it is often beneficial to include acoustically absorptive finishes in spaces used for speech (for example teaching spaces, offices, healthcare facilities) to help control reverberation and, in turn, aid speech intelligibility. Acoustic absorption generally takes the form of acoustic ceilings but can also be introduced as wall panels, baffles or rafts.

The longest reverb

In 2014, acoustics guru, Trevor Cox, set a new world record for the longest echo in a man-made structure in a subterranean oil tank in Inchindown, Scotland. After a single gunshot, the reverberation time was measured as over 112 seconds (more details at **https://www.bksv.com/en/knowledge/blog/perspectives/longest-reverb**)

Institute of Acoustics
Sound • Noise • Vibration

What's so useful about acoustics?

WHAT'S IT ABOUT?

Acoustics is the interdisciplinary science that deals with the study of all mechanical waves in gases, liquids and solids including vibration, sound, ultrasound and infrasound.

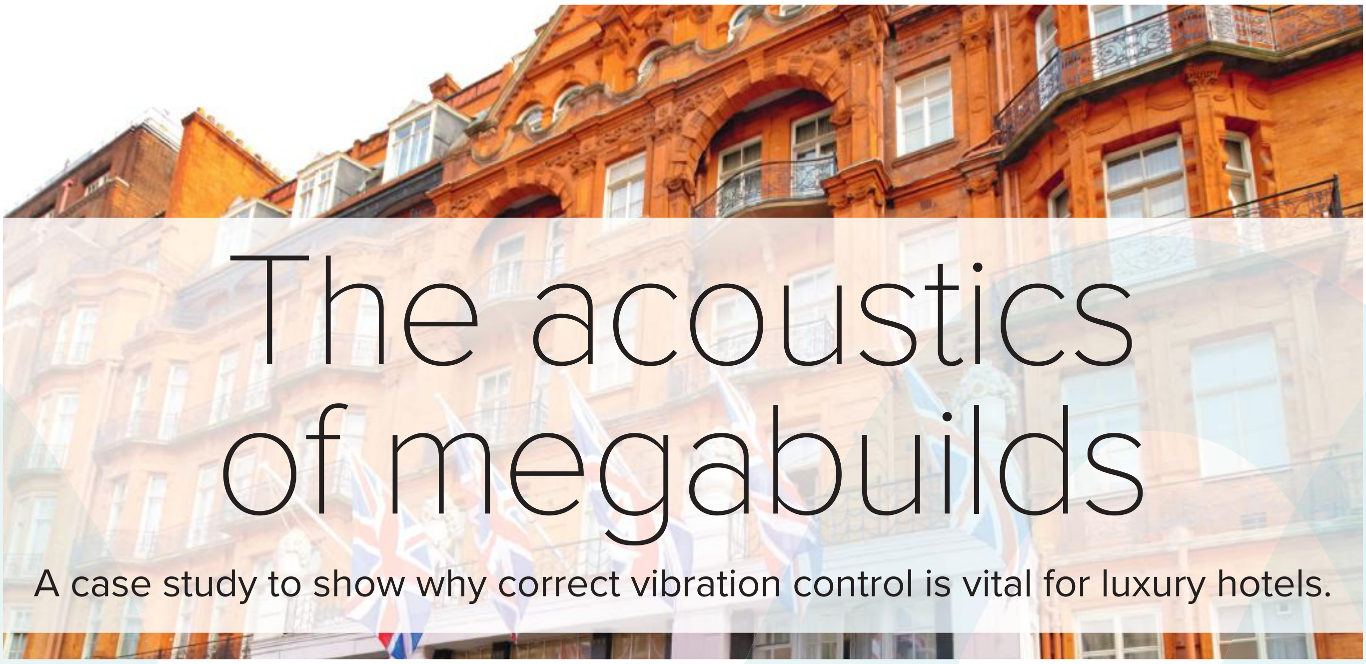
Many people think that acoustics is strictly musical or architectural in nature. While acoustics does include the study of musical instruments and architectural spaces, it also covers a vast range of topics, including noise control, SONAR for submarine detection, ultrasounds for medical imaging, thermoacoustic refrigeration, seismology, bioacoustics and electroacoustic communication.

Professional acousticians work in a huge variety of fields – from the design of a recording studio or smart phone audio apps to environmental and workplace noise measurement and control, and from the assessment of wind farm noise to car and jet engine design, to name just a few.

WHAT IS THE INSTITUTE OF ACOUSTICS?

A professional engineering institution founded in 1974, the IOA is the UK's professional body for those working in acoustics, noise and vibration.

THE SCIENCE OF SOUND, ITS PRODUCTION, TRANSMISSION AND EFFECTS



The acoustics of megabuilds

A case study to show why correct vibration control is vital for luxury hotels.

Above: Claridge's, London

In the recent BBC documentary series, *The Mayfair Hotel Megabuild*, one of the issues encountered on the project was noise from the underground trains resonating through the building, particularly at basement levels. In this article, Adam Fox, whose company, Mason UK, featured in the documentary, explains why acoustics and vibration are a growing problem for many hotels in London and what can be done about it.

The BBC documentary series described the renovation of Claridge's Hotel in London as the "most audacious hotel upgrade ever attempted." For those involved in this project, it was a challenge and a privilege. However, from an acoustics point of view, the challenge encountered here is one that many hotels across the capital face.

As part of the hotel upgrade, a new five story megabasement was created. The documentary shows how during the construction process, Norman McKibbin, Construction Director at the Maybourne Group, discovered that they could hear the hum of tube trains at basement level. As Claridge's sits between three different underground lines, faint vibrations from the tracks 200 metres away were carried through the ground and then amplified by the new basement structure.

The need for quiet

The basement was intended to include silent treatment rooms, where residents would receive massage therapy and enjoy a luxury spa. Ensuring that no noise disturbed this environment was therefore non-negotiable. Norman hired a team of acoustics and vibration engineers, and that is where Mason UK entered the story.

Box-in-box solutions

The solution to the vibration problem was a box-in-box construction. Each inner room was surrounded by acoustic insulation and attached to the existing room with spring or rubber isolators that will absorb the vibration and prevent the sound from travelling.

Although few projects can rival Claridge's' refurbishment for prestige, box-in-box constructions are commonly used for these purposes. The key component is a floating floor, the design of which is determined by the level of isolation required. A jack-up floating floor creates a floating concrete slab supported at regular intervals by either rubber or spring mounts, to create an air gap underneath.

Walls can be isolated, either by being built on the floating floor or specially designed wall plates. The box-in-box structure is complete with an acoustic ceiling or lid. Acoustic ceilings are generally supported on drop rods on acoustics hangers, again rubber or springs are used.

Box-in-box constructions and the acoustic products they require are found in many types of building aside from hotels, including theatres, cinemas and healthcare facilities. However, there is a growing demand for this type of solution as many developers and contractors require excavating basement levels. In London, this often brings the structure closer to the main source of vibration; underground tube tunnels.

Getting the installation right requires experienced engineers and high-quality engineering products. On occasion, it will be necessary to provide bespoke products, to deal with additional challenges like space requirements that were not anticipated in a specification. Getting it right first time is essential, as retrofitting a solution is prohibitively costly and can cause reputational damage, especially in a luxury development. ◎

The unique atmosphere created by music and crowd noise

Benjamin Wiggett, a graduate acoustic consultant for AECOM and a former international DJ, explains why building acoustic design is imperative to a positive experience for the performer, audience and local environment.

Above: Benjamin Wiggett at SubQuake, Tilburg, The Netherlands, 2013 *(Copyright Sylvio Armando Pinas)*

My adrenaline rises as we pass the line of clubbers eagerly waiting outside. The familiar rumble of bass grows, becoming more and more distinct with every step towards the entrance. We enter the foyer and the intensity continues to increase. Conversation is difficult as the drums filter through every opened door. A wall of sound hits us as we head onto the stage. Show time!

We can all picture the scene, whether you're a performer or a clubgoer. When we walk into a venue, the wave of noise and energy can be both exhilarating and overwhelming. The sound of music and crowd noise come together to create a unique atmosphere. Our individual aural experience is directly affected by a venue's acoustic design – whether for better or worse.

Everything plays its part; building materials, room finishes, room dimensions, speaker placement, audience size, and noise limit.

Raving or behaving

If you've ever ordered a drink in one attempt, you probably weren't at a gig of mine. Saying that, if you had to repeat yourself multiple times, the music was obviously too loud. Acoustic design is crucial to creating a comfortable and safe environment both inside and outside the venue. Also, it's not all about the audience or the neighbours, noise poses a serious risk to employees too. Noise legislation exists to reduce the risks associated with noise exposure, mitigate noise nuisance, and improve overall health and safety.

Relatively early in my DJ career, circa 2003, I recall performing in a warehouse rave with a poor sound system and layout. To be honest, the standard of sound may have been acceptable for that era, but I know now there was no science applied by the production team at all. I kept turning up the DJ monitor to hear the tune I was mixing. It was so loud it was distorting badly. Vinyl was the format in our arsenal back then. As it's analogue – every snap, crackle and pop blares out – at levels well over 100 dBA. The damage I did to my ear in a single night was probably irreversible.

The art of sound

Assessing and managing the risk of noise exposure is required under the Control of Noise at Work Regulations (2005), which aims to protect workers from exposure to excessive noise in the workplace. It is a legal requirement for employers to provide hearing protection to staff when exposure levels reach 85 dBA. I've been wearing custom-made earplugs for 20 years now, whether performing at or attending events. I cannot recommend them enough and the protection they provide is priceless. Legislation like the Control of Noise at Work Regulations, exists for every element of acoustic design for a performance space and provides a framework for designers, architects and acousticians to implement their design principles collectively.

In the UK, the standards used for the acoustic design of performance spaces and nightclubs are largely based on the guidelines set out by the Association of Noise Consultants (ANC), the Institute of Acoustics (IOA), and the British Standards Institution (BSI). Some of the specific standards include:

- BS 8233:2014 provides guidance on the control of noise in and around buildings, including performance spaces and nightclubs;
- BS EN ISO 3382-1:2009 provides guidance on the measurement and evaluation of room acoustics parameters, including reverberation time, clarity, and definition;
- Code of Practice on The Control of Noise from Pubs and Clubs, published by IOA, this guide provides practical advice on the control of noise from nightclubs; and
- BS 4142:2014+A1:2019 provides guidance on the rating of industrial and commercial sound. While not strictly applicable to music and entertainment noise, the guidance is still useful to assess noise generated by nightclubs. P68

Left:
Benjamin Wiggett at Homegrown, Cape Town, South Africa, 2012
(Copyright John Henry)

Often, bespoke criteria are used; combining relevant guidance to meet the client's needs.

These standards and guidelines provide a framework for the acoustic design of performance spaces and nightclubs in the UK, helping to ensure that they provide optimal sound quality while minimizing noise impact on the surrounding environment.

It is critical to consider the design of the acoustic environment, including looking at the architecture of the space, the soundproofing (sound insulation) materials used, and the placement of loudspeakers or other audio equipment. Acoustics and noise control measures typically include the installation of acoustic barriers (to block noise at the source or at the receiver), absorbers (to reduce the number of sound reflections in a space), and diffusers (to increase the 'scattering' of sound to create a more diffuse space). Additionally, the sound system can be designed and adjusted to achieve a desirable noise level. With consideration for relevant guidance and legislation, a nightclub can be designed in such a way as to create a vibrant and fulfilling atmosphere without introducing health risks, noise nuisance or running afoul of the law.

The power of acoustics

When performing, the bass in the DJ booth can be overwhelming and the room itself can play havoc with bass frequencies. Room modes (or loud spots) can often be due to problematic frequencies forming standing waves. This is where soundwaves bounce between reflecting surfaces (usually a wall, floor or ceiling) constructively interfering with each other. The effect is a series of bass-heavy hotspots around the room. In theory, the same physics can be used to 'cancel' these waves out — much easier in theory than applied to a nightclub in full swing.

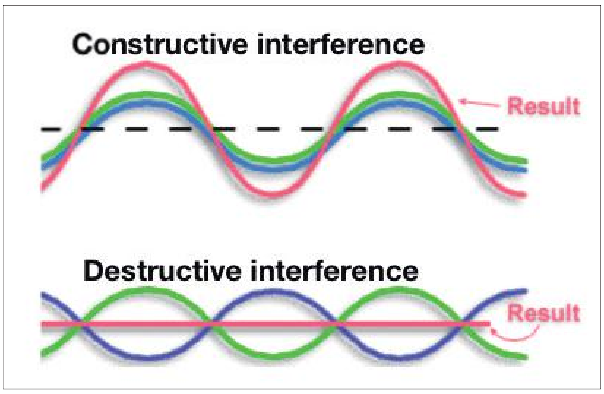
The sound of bass that used to echo from town centres in days gone by is seldom heard now. This was partly due to clubs not meeting local authority noise regulations. This is where building acoustics plays a vital role in the refurbishment of existing clubs that have been part of the communities and culture for generations, or indeed, part of the planning process of building new state-of-the-art clubs that will inspire the next generations of artists.

From a performance perspective, compensating for excessive bass can be difficult. Adjusting the bass lower on the mixer solves the problem for me (and maybe the neighbours) but significantly reduces the impact on the dancefloor. To reduce the transmission of sound from the main room, concrete walls, air gaps and acoustic springs/mounts can be used. These make it more difficult for sound to travel through each material and be re-radiated on the other side.

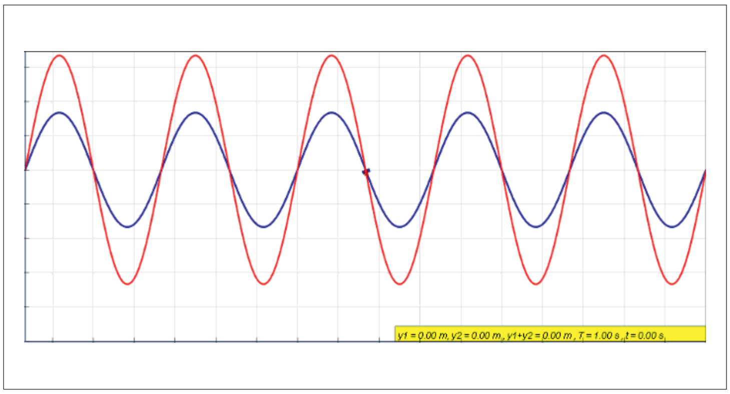
Another important factor for noise control is the use of sound-absorbing materials in the venue. These materials help to reduce echoes and reverberations, which can cause the sound to bounce around the room and interfere with the clarity of the music. Weirdly, the audience themselves act as a pretty good absorber for some of the higher frequencies, (the larger the audience, the greater the absorption coefficient), but larger wavelengths (bass notes) require more thought.

The sound of success

From a DJ's perspective, sound quality is essential as it can make or break their performance. It's a pleasure to perform in a venue where the clarity of sound is crystal



Above: https://www.fizzics.org/standing-waves/



Above: https://commons.wikimedia.org/wiki/File:Waventerference.gif clear. Performing in a world-class nightclub, with optimal acoustic conditions can give the DJ confidence to mix with full control, trust their ears and encourage creative freedom. A well-designed acoustic environment can enhance the clarity and definition of the music, making it easier for the DJ to mix and for the audience to appreciate the nuances of the performance. This in turn transcends onto the dancefloor, creating energy and connection. The atmosphere alone becomes a memory for both the DJ and the audience. These are the moments that DJs and performers crave.

In contrast, a poorly designed acoustic environment can have the opposite effect. The music can become distorted and muddled, making it difficult for the DJ to mix effectively and for the audience to fully engage and connect with the performance. This can lead to a lack of energy and excitement and ultimately detract from the overall experience. The acoustic design of the space plays a significant role in shaping the overall tone and it can have a profound impact on the performance's success. By understanding the importance of acoustic design and taking steps to optimise the space accordingly, both DJs and nightclub owners can create a thrilling and memorable environment for everyone involved. Properly placed acoustic panels, curtains and carpets can all contribute to a better sound experience. Ultimately, this creates a sense of immersion and connection between the DJ and the audience, heightening the energy and excitement of the night. It isn't all about loudness!

Media links

Drumsound & Bassline Smith v Utah Saints — What Can You Do For Me — **https://www.youtube.com/watch?v=9CjHKPKgZ7Y**

Drumsound & Bassline Smith — Through The Night ft. Tom Cane **https://youtu.be/S85q2xSpwUI**

About the author:
Benjamin Wiggett was a founding member of the Drum & Bass collective Drumsound & Bassline Smith who achieved two UK Top 40 singles in 2012. He was an international touring DJ for 20 years and before studying for a BSc in Music Technology and Production at the University of Derby. He also conducted sound design and audio post-production for independent film producers and game developers before pursuing a career in acoustics.

Designing for acoustic satisfaction in open plan offices

Environmental satisfaction in work places is closely associated with comfort and productivity, but it turns out to be quite a challenge to get the design spot on. This article shows how to understand acoustic satisfaction in open plan offices, and how we align design processes to achieve the desired outcomes.

By Jack Harvie-Clark

The Leesman Index is the world's largest employee workplace experience survey and it has been telling us for over a decade[1] that in open plan offices:

- dissatisfaction with noise levels kills productivity (importance rated around 70%); and
- average satisfaction with noise is only around 36%.

The noise problem is one of the hardest for organisations to crack and so it's down to acousticians to improve the working conditions of many people.

Below left: Figure 1: Traditional office layout

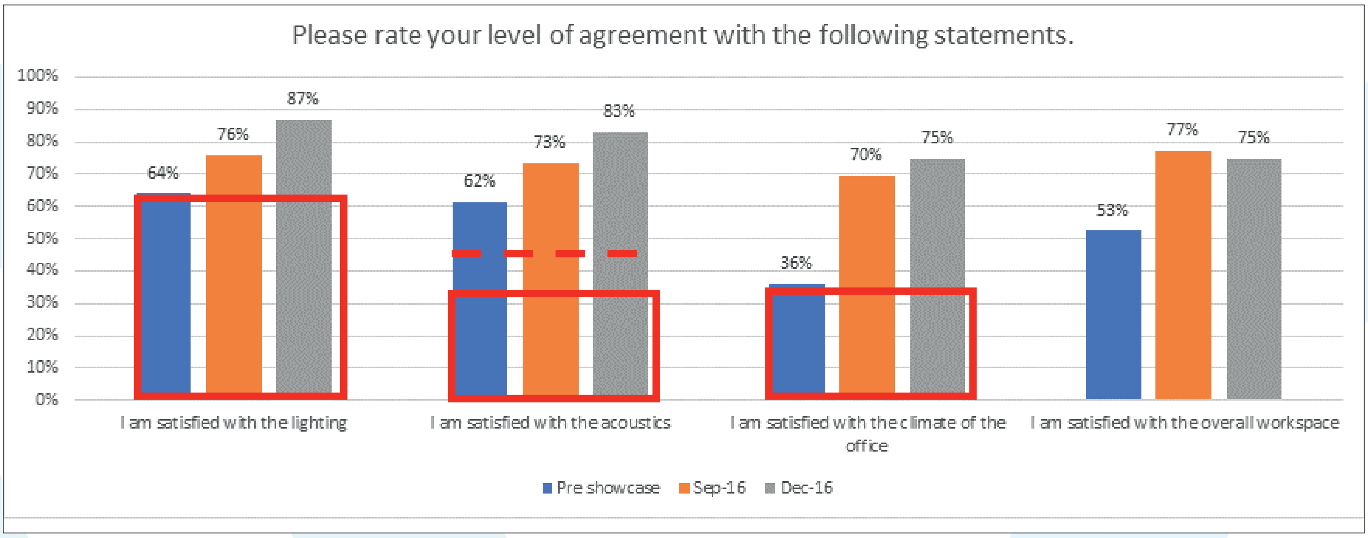
Below right: Figure 2: The same office building with re-designed furniture

Case study on acoustic satisfaction

This was an office transformation project to facilitate new ways of working. The traditional office is shown in Figure 1, with rows of assigned desks arranged perpendicular to the façade. Figure 2 shows the same building, where there has been no change to the ceiling, facade, lighting, or HVAC system — but the furniture has been re-designed to support the new ways of working.

Footnotes

1. https://www.leesmanindex.com/a-decade-of-change/



Above:
Figure 3:
Results of staff surveys on traditional and new ways of working floorplates, compared with Leesman global benchmarks

In the traditional layout there are few meeting rooms so informal meetings just convened at people's desks. In this project, they had a strong change management programme that included management by results rather than presenteeism. As part of this change, they had to change the office landscape so that nobody had an allocated place, people were encouraged to find a place to work that suited their task in hand.
Following the transformation, surveys revealed that staff members were so much happier with the acoustics in the new office that the organisation wanted to replicate this in their design and specification for future offices. So the room acoustic response in the old office, coupled with the new ways of working were measured according to ISO 3382-3; to include conditions when the offices were occupied, the ambient noise and the liveliness[2] were also measured.

But the measurements taken did not distinguish any significant difference between the old and the new offices. However, the staff could clearly distinguish the difference, not just for their satisfaction with the acoustics but also with their satisfaction with the lighting and thermal comfort, as shown in Figure 3. (The term 'pre-show-case' refers to the traditional office layout. The surveys carried out in September and December 2016 were on the 'show-case' floor plate, which adopted the new ways of working.)

In the traditional office, satisfaction with the lighting and thermal comfort were almost exactly on the global benchmarks according to Leesman, whereas satisfaction with the acoustics was already much higher. This may be because the question is asked slightly differently — Leesman asks about 'satisfaction with noise levels,' whereas in this questionnaire they were asked about 'satisfaction with the acoustics;' people may respond differently to the different question.

Satisfaction with the lighting and thermal comfort improved significantly, as well as the satisfaction with the acoustics. And yet neither the lighting nor HVAC system changed, and no difference in the acoustic conditions in the room could be measured.

This case study demonstrates very powerfully how people experience an improvement in their environmental satisfaction when they have more control over their environment[3].

How important is control for acoustic satisfaction?

Psychological literature tells us that a level of 'control' is essential for an individual's wellbeing, and that it's a psychological and biological necessity[4]. In building services the importance of control is well known, and is described as a 'killer variable' for comfort and productivity[5]. A 'killer variable' means it's a key indicator; people's sense of comfort and self-rated productivity are strongly dependent on how much control they feel they have in a building.

Strength of acoustic indicators to predict acoustic satisfaction

Of the indicators in ISO 3382-3, the only one that is statistically significantly associated with noise annoyance is the distraction distance[6]. In presenting the accumulated data between distraction distance and disturbance by noise, the authors knew that control was important. The four offices where the occupants either had an opportunity to use a protected quiet room or they were activity-based working (ABW) offices are P72

Footnotes

2. Proposed Method For Measuring 'liveliness' In Open Plan Offices. Sara Vellenga, Tom Bouwhuis, Theodoor Höngens. ICSV24, 2017.
3. The value of control for acoustic satisfaction in open plan offices: a case study. Jack Harvie-Clark, Richard Hinton. ICBEN 2021.
4. Born to choose: the origins and value of the need for control, Lauren A. Leotti et al, Trends in Cognitive Sciences, 2010.
5. Productivity in buildings: the 'killer' variables. Adrian Leaman & Bill Bordass, Building Research & Information, 1999.
6. Distraction distance and perceived disturbance by noise—An analysis of 21 open-plan offices. Annu Haapakangas, Valtteri Hongisto. JASA, 2017.

marked with a different symbol. These are the offices where people had more control, and don't seem to follow the same trends as the rest of the data.

New acoustic narrative required

Our case study office can't be plotted on that chart due to the questions being asked differently, but the change in acoustic satisfaction might have moved it from around the middle of the chart, towards the peripheral data amongst those ABW offices.

It's important to remember at this point that we have no acoustic diagnostic tools to even understand how the acoustic satisfaction was improved. It's not part of the acoustics narrative. What we really need is a new framework that can describe acoustic satisfaction in its entirety. That sounds like an ambitious prospect but it already exists, just not in acoustics for open plan offices.

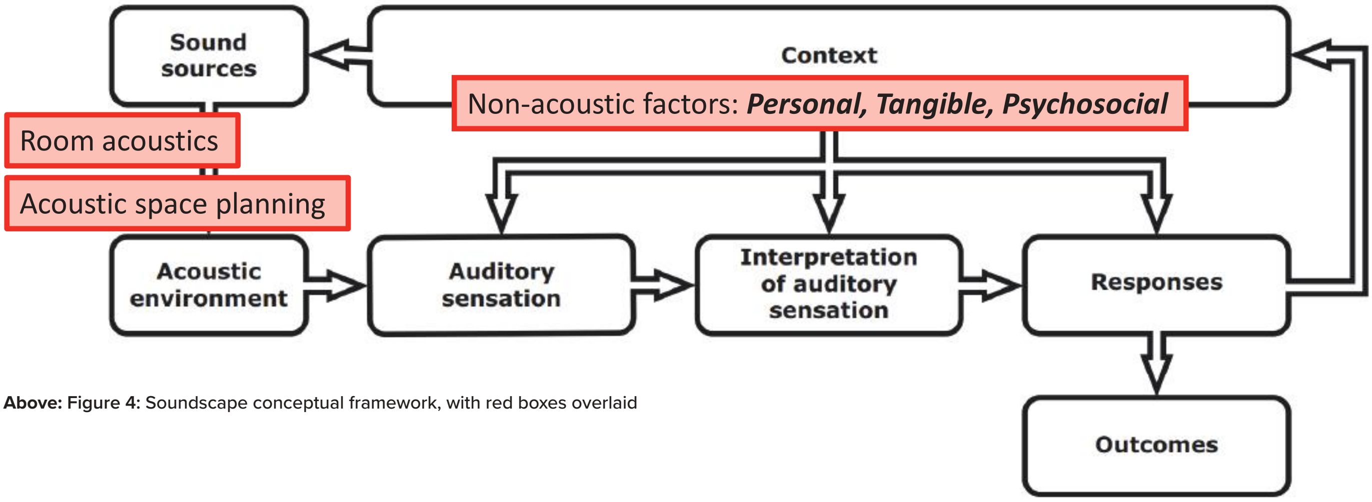
The soundscape framework

The soundscape framework has been developed to describe people's experience of sound holistically, in context. The ISO 12913-1 Standard was published in 2014, with the conceptual framework as shown in Figure 4. Also on Figure 4 are annotations of where the room acoustics and acoustic space planning fit in. The room acoustics are described by the indicators in ISO 3382-3 - this is the way that the empty room responds to sounds within it - the most notable indicator being the distraction distance, denoted r_D. The acoustic space planning refers to the process of planning the different occupancy locations or zones - to avoid acoustic conflicts; these typically occur between people who talk frequently - either because they are extrovert types, or their job requires it (e.g. a contact centre or IT help desk), and people who work mostly without conversing.

Non-acoustic factors

The larger part of this diagram is given over to 'context' and this refers to the non-acoustic factors. The non-acoustic factors are all the things apart from the sounds that affect people's experience of sound. The non-acoustic factors are starting to be documented and categorised as either personal, tangible, or psycho-social factors[7]. Some of the most advanced work to describe and document non-acoustic factors is currently taking place for aviation noise[8]. In this field, researchers have determined that one-third of the variance in annoyance reactions is due to acoustic factors, another third of the variance in annoyance can be explained with non-acoustic factors, with the final third currently unexplained. As it cannot be explained with the acoustic factors, this means that there are non-acoustic factors that are yet to be accounted for.

Personal factors are things like noise sensitivity, capacity to cope, perceived control and perceived fear. These are associated with an individual and are relatively stable over time. Tangible factors (sometimes called environmental factors) are factors relating to the environment rather than the individual. For example; 'visual modifiers' — looking at foliage or trees rather than looking at a road, the road traffic noise is perceived as less annoying. It is also established that road traffic noise



Above: Figure 4: Soundscape conceptual framework, with red boxes overlaid

Footnotes

7. Development of a new ISO Technical Specification on non-acoustic factors to improve the interpretation of socio-acoustic surveys Benjamin Fenech, Lisa Lavia, Georgia Rodgers, Hilary Notley. ICBEN 2021.
8. Coping with Aviation Noise: Non-Acoustic Factors Influencing Annoyance and Sleep Disturbance from Noise. Susanne Bartels et al. (2022) Aviation Noise Impact Management.

is less annoying if there is access to green space within a five minute walk of the home.

Psycho-social factors are described in acoustics literature as factors which are shared between members of a community — qualities such as perceived fairness, perceived community benefit from the sounds and attitudes towards noise authorities. A new ISO Technical Specification (ISO/TS) on non-acoustic factors has been proposed to improve the interpretation consistency of socio acoustic surveys[8].

Non-acoustic factors in open plan offices

It might seem as if a whole new branch of science is required to investigate non-acoustic factors in open plan offices, but in fact much of this work has already been carried out in this area — just not described in this way.

The response to noise distraction by different personality types has been investigated[9], demonstrating that extroverted people are more satisfied with noise in open plan offices in both allocated and unallocated settings and that both introverted and extroverted people are less satisfied at allocated desks compared to unallocated desks. Perhaps that's the control factor coming in there as well.

Another study[10] looks at the personal need for privacy and how that affects people's perception of how well an activity is perceived to fit in a particular work setting. The personal need for privacy affects both satisfaction with the work environment and task performance.

This isn't about the need for acoustic privacy — it's about people's personal needs and how well they are suited to different tasks in different settings. We can't necessarily understand an individual's personal factors when they are moving into a new office but we can design for a range of sensitivities and personal needs. Or we can be explicit about the fact that an office may be designed for a limited range of personal needs. We need to understand that two people doing the same task in the same environment will have a different experience of comfort in that place; they will have different needs even when they are performing the same activities, because of their personal factors.

Other personal factors which are important in open plan offices are people's experience and their expectations. A new office implies a change. The study of personal office preferences[11] and other studies have demonstrated that people prefer the work setting that they are already in. People in private offices rate private offices more highly than other types of work settings, whereas people in other types of work settings (open plan, ABW) rate private offices less highly. When people move from private offices to open plan offices, then on to ABW offices, they generally don't want to move back down that path.

We are creatures of habit and we don't like change. Change invokes fear. People's expectations about a new office are very important, as are the way in which people's expectations are managed. A study of a workplace change process and satisfaction with ABW[12] showed that the strongest predictor of the change in environmental satisfaction, a year after the move, was the degree of agreement with the management's reasons for the change.

This can be understood as a psycho-social factor: if you believed your manager's reasons for the change, you felt more comfortable in the new office, and vice versa. We should not underestimate the importance of change management and the way in which that process is carried out. Another study showed that where people thought they were going to have more impact on the design than they did, they felt disappointed with the new office and consequently felt less comfortable in it.

Can you improve our acoustics?

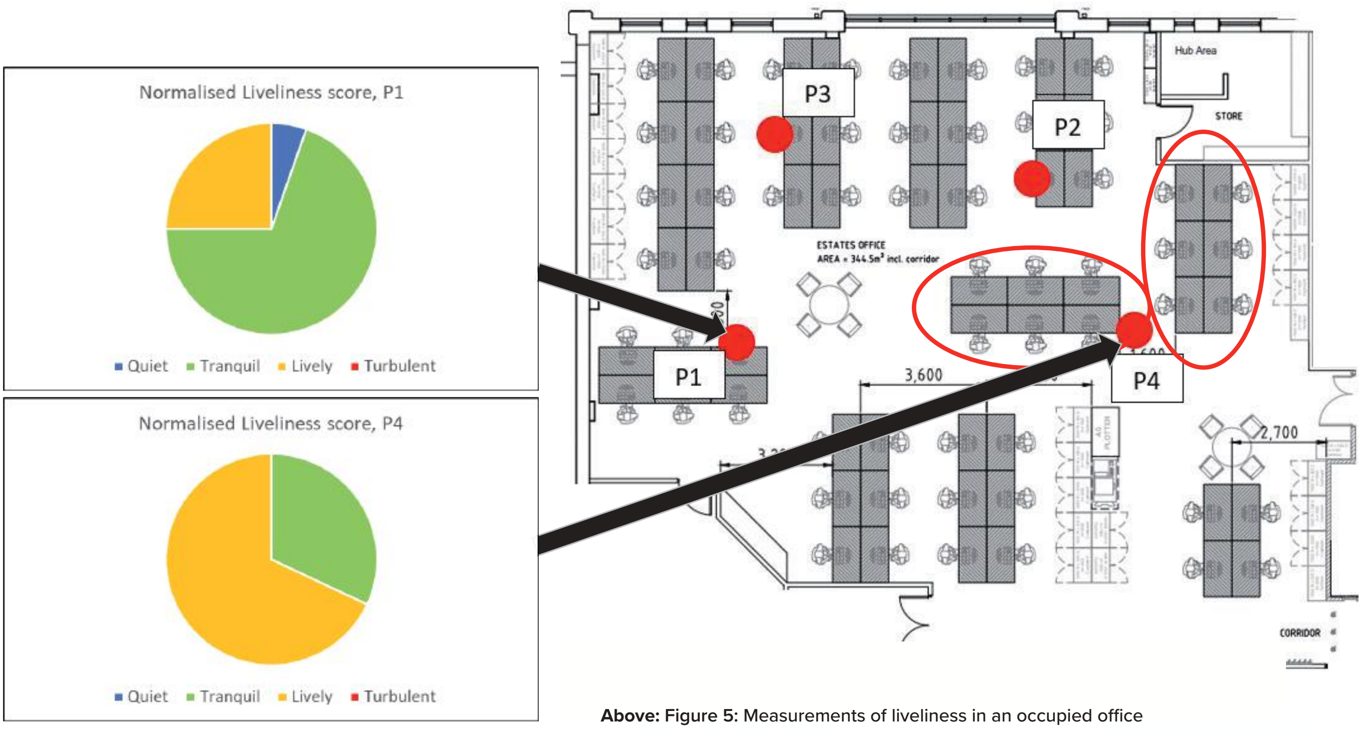
In another case study that we carried out, our client asked how can we improve the acoustics in their office and we threw everything at it. We visited when the office was unoccupied, and we measured the ISO 3382-3 room acoustic indicators. We visited when it was occupied and measured ambient noise and liveliness[2]; and we used a noise comfort questionnaire to ask people about their experience.

The data that was most useful to us were the observations we made when we were taking the attended measurements and talking to people about their experiences in this office.

The people that sit at the middle table simply like to chat more— they are doing the same type of work as people in other parts of the office but they're more sociable or extroverted perhaps. This was demonstrated in the measured results for liveliness, as shown in Figure 5. On the left hand side of the office it was tranquil most of the time, whereas on the right hand side of the office, it was much more lively for most of the time. The table seating people who prefer to talk while they work impacts on the people sitting around them. Talkative people need a protected area of the office without disturbing others around them; which requires specific acoustic space planning. P74

Footnotes

2. Proposed Method For Measuring 'liveliness' In Open Plan Offices. Sara Vellenga, Tom Bouwhuis, Theodoor Höngens. ICSV24, 2017.
8. Coping with Aviation Noise: Non-Acoustic Factors Influencing Annoyance and Sleep Disturbance from Noise. Susanne Bartels et al. (2022) Aviation Noise Impact Management.
9. The response to noise distraction by different personality types: An extended psychoacoustics study. Nigel Oseland & Paige Hodsman. Corporate Real Estate Journal, 2020
10. Perceived fit in activity-based work environments and its impact on satisfaction and performance, Hoendervanger et al, J. Environmental Psychology 2019
11. Personal office preferences, Nigel Oseland, 2019.
12. Workplace change process and satisfaction with activity-based office. Pia Sirola et al, Facilities, 2020



Above: **Figure 5:** Measurements of liveliness in an occupied office

Could this situation have been predicted during the planning of this office? We don't think so. This is a type of insight and intervention that can only be revealed in an operating office to improve the acoustic conditions. This demonstrates that the acoustic design should not be considered 'complete' when an office is handed over; as people learn to use the office, there are always interventions and changes that can be made to improve the acoustic conditions.

The noise comfort questionnaire revealed that the sound of telephones ringing was a significant problem. Further investigation indicated that the six desks on the far right hand side are sometimes used as a contact centre. Telephones don't need to ring these days — operators can use light indicators and turn the volume right down. A few simple changes that were indicated and led by the occupants, improved acoustic conditions without changing the room acoustic indicators measureable with ISO 3382-3.

Change the narrative

So we need to change the narrative — acoustic satisfaction does not exist in the room, it's in people's minds. To design for acoustic satisfaction we need to take room acoustics out of the equation and address the people who are using the office. We need to understand their range of needs, and design the accommodation so that they enjoy a degree of agency in controlling their choice of space that suits their needs.

We need participatory design processes and to find out what people need. Acoustic design should not stop when the building is handed over. A new office is like a tool — it takes time to learn how to use it. Not many engineers would design a bespoke new tool without engaging with the users. Each one is like a prototype — its use can always be improved by reflecting on how it's used, observing and understanding from the users what the issues are, and improving those places where there's acoustic conflict.

Everything we do must be in the context of our sustainability crisis. We can't afford to keep designing workplaces that don't work for people: it's a huge waste of our resources.

Conclusion

The science of acoustics in open plan offices has made great advances with the room acoustic indicators in ISO 3382-3. These are necessary but not sufficient to explain occupants' acoustic satisfaction. We need to take account of the diversity of people who will use an open plan office, and the activities that they will perform. We need to take their experience and expectations seriously if we want them to be more comfortable in a new office. We need to give people a genuine sense of control over their environment, so that they can be confident of finding a suitable place for the variety of tasks that they perform. If we don't do this, people will attend the office reluctantly; both the organisation and the individuals will lose the benefits that can be gained by collaborative working with colleagues. Human-centric design already exists; this needn't be reinvented; we just need to include acoustics in those processes as much as a human factor as a technical factor.

Above: Many people find the acoustic environment in open plan offices can significantly impair their ability to work; so they use a range of coping mechanisms, or avoid the office as much as possible

Exploring the cultural heritage and restoration of Notre-Dame Cathedral through acoustic digital reconstructions

The acoustics of a place are ephemeral, but they are intrinsically connected to the physical environment. With acoustic measurements, acoustic models, and extensive archival research, acousticians are reconstructing the sounds of Notre-Dame through the ages after it was damaged by fire on 15 April 2019.

By Sarabeth S. Mullins, Elliot K. Canfield-Dafilou and Brian F.G. Katz

The modern experience of profound historical architectural achievements such as Etruscan tombs or Gothic cathedrals is strongly linked to each site's acoustic environment. The acoustics of an ephemeral heritage site are an intangible consequence of the tangible construction and furnishing of the space.

The echo of the cathedral

With the recent adoption of the UNESCO resolution on the importance of sound, in addition to the Convention for the Safeguarding of the Intangible Cultural Heritage, awareness is now growing of the importance of preserving, studying, and recreating the soundscapes and acoustics of historical sites. At the same time, the rapid development of available computing power has allowed for acoustic simulations capable of modelling vast and complex buildings in which acoustics often play a crucial role, such as theatres, concert halls and cathedrals.

While Notre-Dame has burned before, the 2019 fire is a reminder of the fragile nature of our cultural heritage. Fortunately, acoustic measurements made prior to the fire preserved the sound of this grand cathedral – and to a certain extent, preserved it. What's more, the application of these measurements creates tools allowing archaeologists, historians, musicologists, and the general public to discover the lost acoustics of the damaged site. As part of the European Past Has Ears (PHE) and the French Past Has Ears at Notre-Dame (PHEND) research projects, and in conjunction with the acoustics working group of the Chantier Scientifique de Notre-Dame, we have been investigating the acoustic heritage of the cathedral over the centuries.

The contemporary acoustics of Notre-Dame

Despite the notoriety of the cathedral, there are few examples of published data on the acoustical parameters of this space. While some previous studies had been published in the early 21st century [Hamayon, 1996, Mercier, 2002], these reported varying reverberation times for the modern cathedral (e.g. 7.5 s and 6.5 s at 500 Hz, respectively), and did not fully explain the measurement protocols used. However, members of our laboratory carried out two previous measurement campaigns before the 2019 fire. After the fire, we were also able to make further measurements to document changes to the building's acoustic state. The plans from these three measurement campaigns are shown in Figure. 1. The first of these, from 1987, was recovered from an acoustic study conducted about a potential organ. While a variety of stimuli were employed, only a few balloon-burst sources were exploitable due to a lack of excitation stimuli details (e.g. anechoic signals, sweep stimuli parameters). While not an ideal omnidirectional source, balloon bursts are valuable in certain situations, offering a portable impulsive source [Pätynen et al., 2011]. The recorded bursts were digitised from the original analogue tape and analysed.

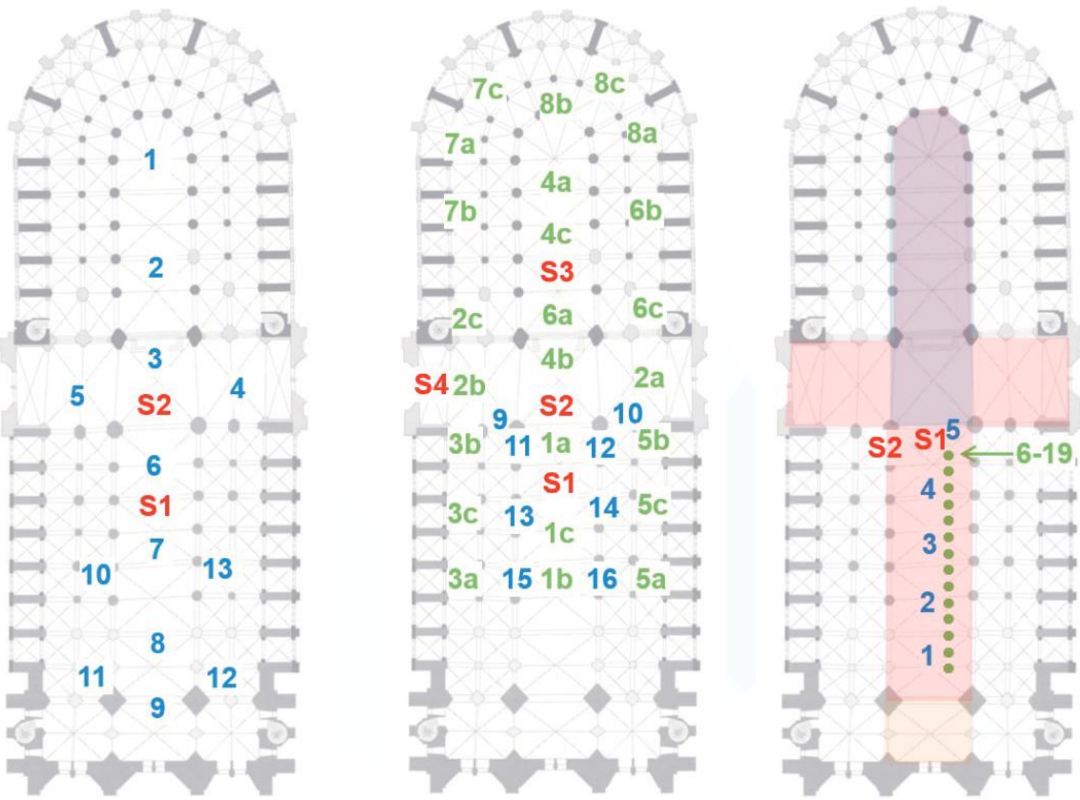
Later, as part of a French research project on Binaural Listening (BiLi), we made a series of acoustic measurements in 2015 almost four years to the day before the 2019 fire. These detailed measurements were made with the modern sine-sweep technique Farina [2000], with multiple receiver positions spread over a large portion of the floor area, including binaural and ambisonic microphones at select positions (see Figure 2a).

After the 2019 fire, access was granted to the construction site for the third measurement campaign, carried out in June 2020. The spire had damaged the central part of the transept/altar marble floor as it fell. Due to the risk of further falling debris and structural instability, the central nave and transept were off-limits to people, as highlighted in Figure 1c. The choir area was likewise cluttered with debris, and therefore inaccessible. Many of the side altars had been used to store objects. There was also scaffolding installed for the removal of the organ and a protection barrier (construction fencing and waist-height perforated metal panels) surrounding the central nave. See photos in Figure 2b; a short video documenting the measurement session is available online[1] .

Comparisons between the results of the two pre-fire sessions (1987 and 2015) show a slight, but significant, reduction in reverberation time (8%), which is likely attributed to the installation of a carpet runner in the 1990s to reduce the footfall noise of circulating tourists. Compared with the 2015 data, the reverberation time after the fire has decreased significantly (20%) [Katz and Weber, 2020]. P78

Below: Figure 1: Measurement plans for the three sessions at the Cathédrale Notre-Dame de Paris

Below: (a) 1987 **Below:** (b) 2015 **Below:** (c) 2020



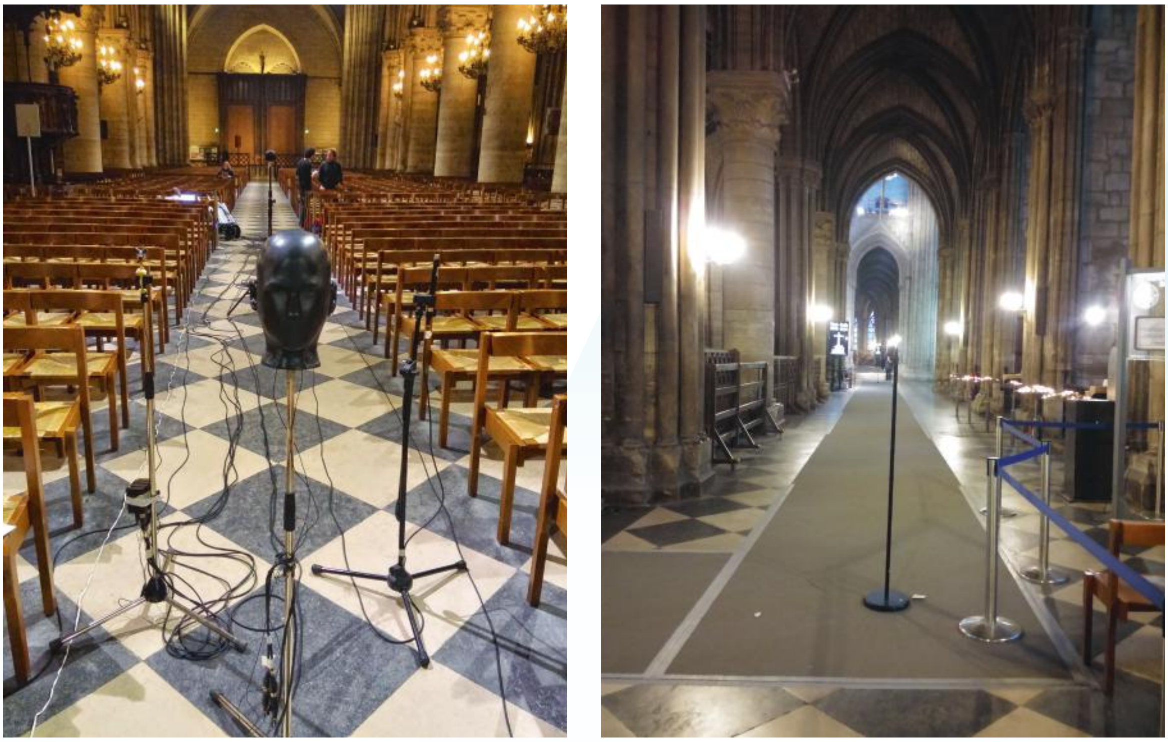
Positions are centred under numbered source (S# (red)) and microphone (# (blue and green)) labels or at points when the measured grid is too dense. The 2020 plan (c) also indicates in shaded regions the scaffolding (yellow), people exclusion (red), and encumbered/damaged ground (blue) exclusion zones where it was not possible to place measurement equipment

Footnotes

1. https://youtu.be/YLi7ASosKvw

Figure 2: Images highlighting conditions for the (a) 2015 and (b) 2020 measurement sessions

Right: Figure 2: (a) 2015, highlighting measurement equipment in the central aisle of the nave and carpet runner in a side aisle during the measurement session



Right: Figure 2: (b) 2020, highlighting the remote-controlled robot-pulled microphone tripods and the general empty state of the nave during the measurements

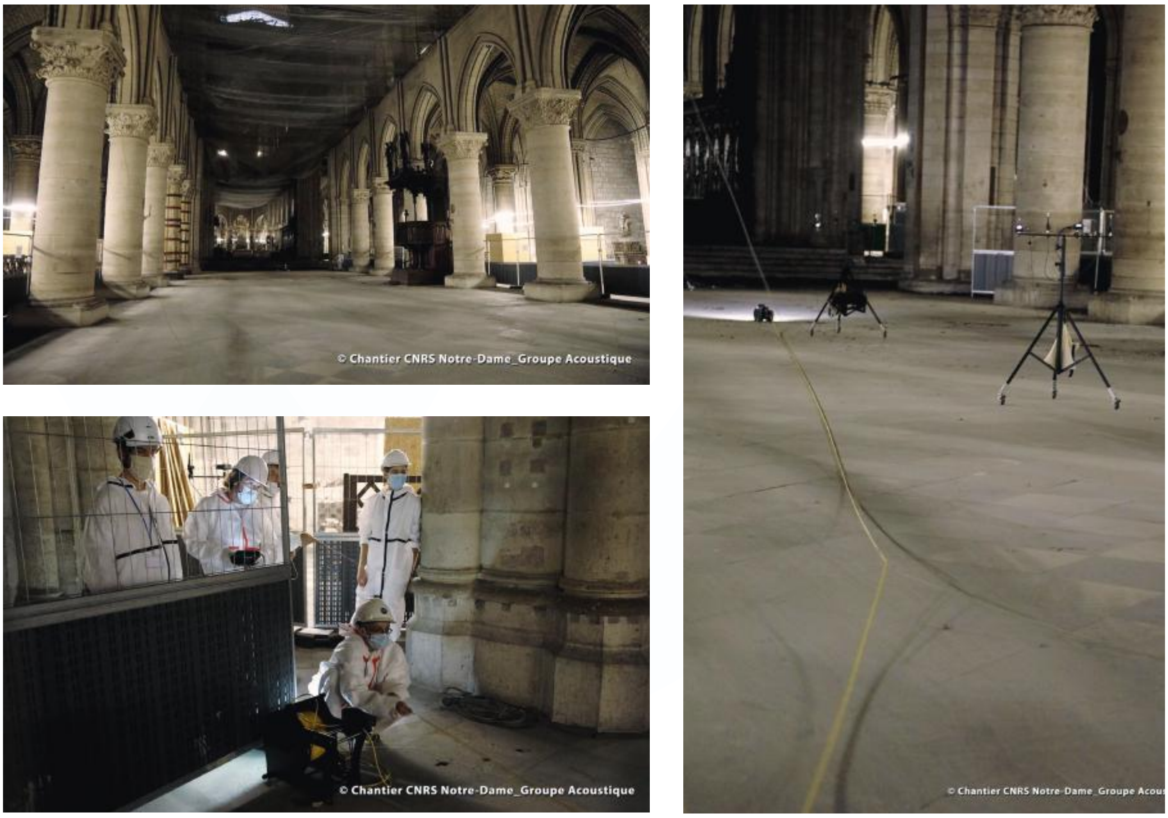
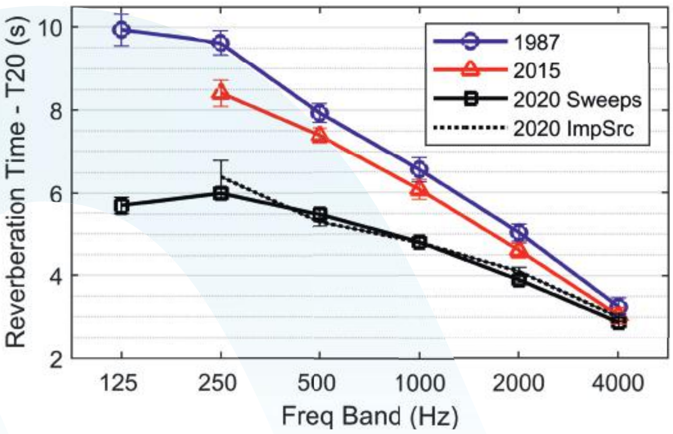
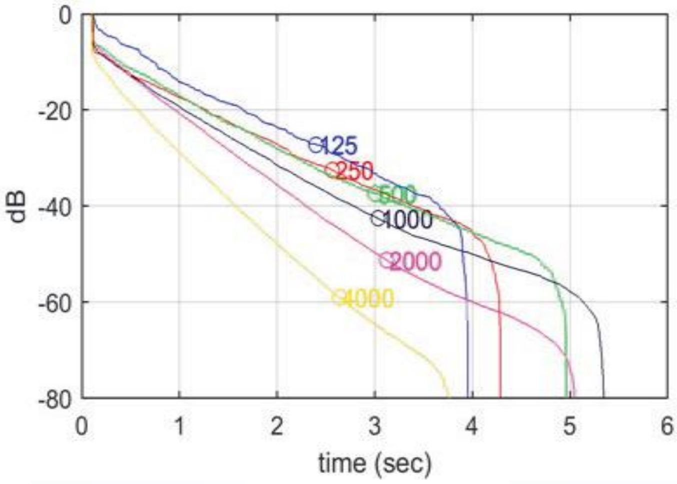


Figure 3: Summary of (a) mean reverberation time over receivers, (b) example RICs, and (c) coupled volume analysis



Above: (a) Mean reverberation time (T20) over omnidirectional microphones with standard error bars. 2020 results show those for sweep stimuli (S1) and impulse source gun-shots (S2, Rec positions 1-5)



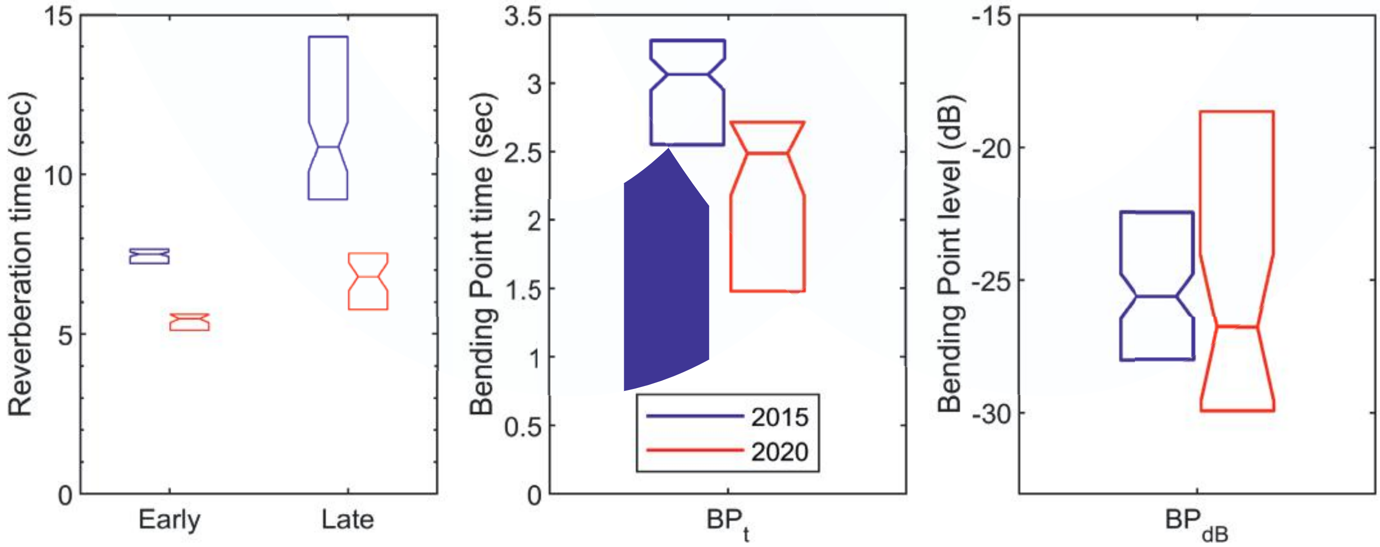
Above: (b) Example of octave band filtered RIC decays, normalised, optimised SNR truncation, 2020 sweep stimuli data-set

We have examined the 2015 and 2020 results for comparable source and receiver positions using the marching line multiple slope analysis method [Luizard and Katz, 2014, Weber and Katz, 2019], in the 500 Hz octave band filtered RIRs (see Figure 3c). One can see the general decrease in reverberation times indicated in Figure 3a, while highlighting the problem of using the ISO3382 standard parameters when non-linear decays are present. Analysis results show a decrease in both Early and Late decay rates, indicating reductions in both the primary and secondary 'volumes'. In the case of Notre-Dame, the delimitation of the different acoustic volumes is not as stark and evident as in coupled reverberation concert hall designs. However, the transept neatly separates the cathedral into two acoustically distinct zones, as its high ceiling and lack of subdividing walls creates a 34m wide by 14m deep by 33m tall zone of free-field propagation between the multilevel eastern and western portions of the cathedral. The reduction in decay rates in these volumes also decreases the bending point time and, to a lesser extent, level. It is noted that all of these parameters are linked to the acoustic coupling conditions. The variability in Late reverberation times for the 2015 condition could be attributed to the complexity of the space, and the various acoustic zones, leading to more than a simple double-slope decay with higher-order coupling.

When the reconstruction of the spire, roof, and vaulted ceiling is completed, and the interior scaffolding removed, we look forward to assessing the next iteration of this monumental building's acoustics.

Simulating the cathedral through the ages

There is a tendency among modern visitors to conceptualise a cathedral as a still and constant witness to history. However, the societies that maintained the P80



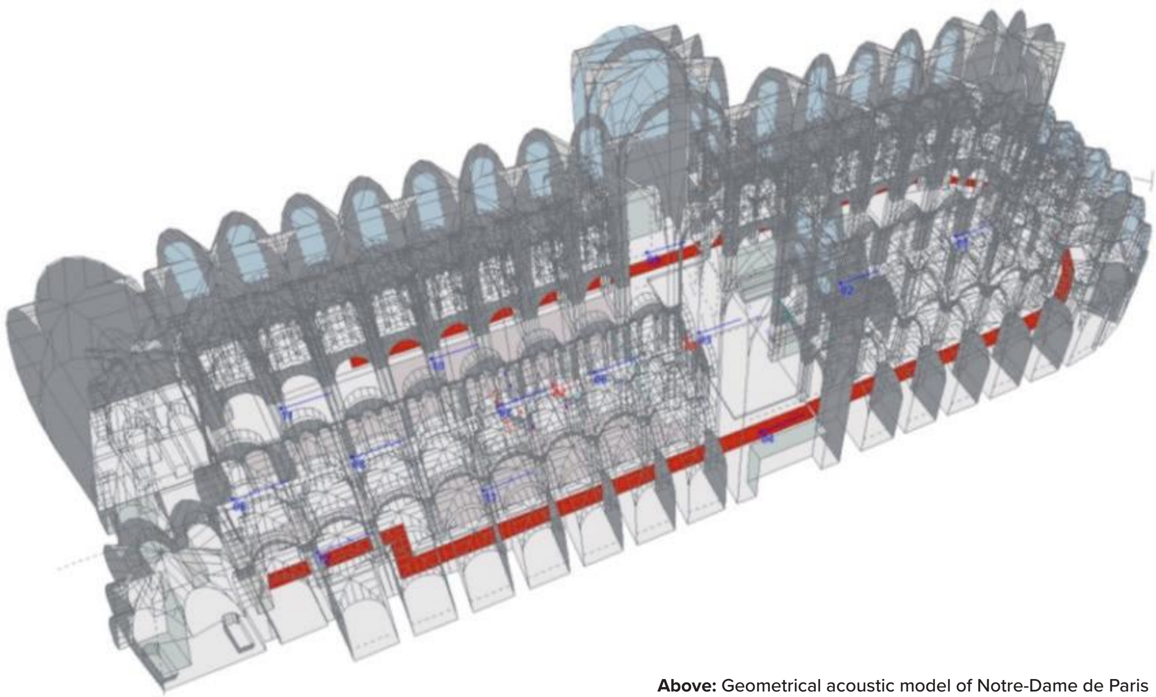
Above: (c) Double-slope decay 500 Hz-octave band analysis distributions showing Early and Late reverberation times and the relative time (BPt) of the identified bending point in the RIC decay curves ([Luizard et al., 2015] for parameter details). Notched boxplots show the median, 95% confidence interval, 25th and 75th percentiles of the data spread building over centuries have all left their marks on the cathedral, from architectural renovations to politically-motivated redecorations, re-purposings, and damages. To modify the cathedral is to participate in a cultural legacy of continuous change.

While physical and digital simulations have been used for decades, digital approaches used in the 20th century were initially limited in their utility. As recent studies have shown the improved reliability of numerical simulations for studying complex, coupled acoustic conditions [Weber and Katz, 2019], we can expect such analytical efforts to be credible for Notre-Dame. We have shown in previous studies that geometrical acoustic simulations (CATT-Acoustic/TUCT) can be perceptually comparable to in-situ recordings [Postma and Katz, 2016b].

A geometric acoustic model of the cathedral was thus created and calibrated on the basis of measurements taken in 2015. Subsequent work on the historical acoustics of Notre-Dame has refined this computer model, featuring alterations in interior geometry, closure of lateral chapels, inclusion of the clôture and rood screen, reshaping of choir stalls, and other details. Additional measurements of historical materials and supporting archival documentation are used to modify the simulations, adapting the model to the cathedral's historical or future states. To date, 13 acoustic models spanning the time period from before Notre-Dame was built in ca. 1163 CE to ca. 1712 CE have been created using this same software (CATT-Acoustic v9.1, TUCT v2.0, see Figure 5a).

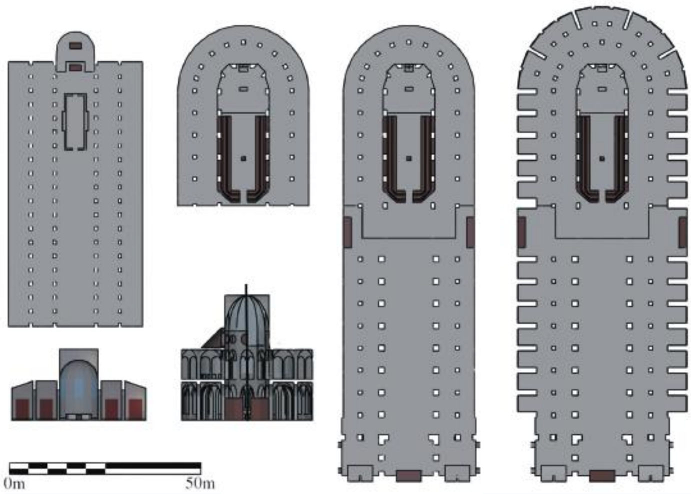
The ca. 1163 model is a speculative one based on the foundations of a massive basilica found in archaeological digs in 1847 CE [Hubert, 1964, Barbier et al., 2019, Sandron, 2021]. Acoustic measurements and architectural plans of an extant and contemporaneous building of a similar architectural style [Cirillo and Martellotta, 2005] were used to create a calibrated model of the stand-in church, which was then modified to match the architecture of the ruins below Notre-Dame. All models after ca. 1163 CE are based on the GA model reported in Postma and Katz [2016a] and subsequently modified to match the historical states as discussed in Mullins et al. [2022], Canfield-Dafilou et al. [2022, 2023]. These models allow us to examine the acoustic evolution of the cathedral over generations, yielding insights into the experience of previous societies at the church.

Figure 4: Several acoustic simulation models and overview of reverberation time results

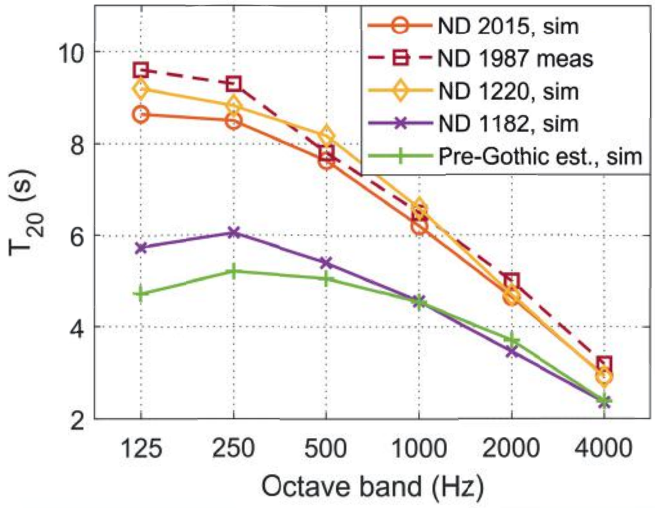


Above: Geometrical acoustic model of Notre-Dame de Paris

Figure 5: Overview of several simulation models and associated reverberation time results



Above: (a) Plans and elevations of ca. 1163, ca. 1182, ca. 1225, and ca. 1350 states



Above: (b) Summary of mean reverberation time

Listening to the past

This type of historically-informed simulation can be a powerful tool for historical studies, providing researchers with a sensory presentation of sound that was previously only available through description and supposition.

In parallel with the construction of the cathedral, a new genre of music developed among the musicians of Notre-Dame. Known as the École de Notre-Dame, these composers and musicians pioneered a virtuoso style of singing that embellished established melodies with prescribed and notated polyphonic ornamentation.

Working with musicologists, acoustic simulations are used to study the potential relationship between these musicians and the reconstructed acoustics of Notre-Dame and its predecessor. These experiments use real-time, immersive virtual acoustic environments to allow singers to perform as an ensemble in the different simulated acoustic conditions. A choir specialising in medieval singing was studied as they sang *Organum Purum* and *Organum Notre-Dame* in the varying acoustics.

Analysis of musical parameters extracted from their recordings helps to examine what influence the different architectures may have had on musicians' performances. Listening tests with specialists focus on the differences in the suitability of music styles to the historical acoustic conditions. In this way, we hope to provide a new level of insight into the interconnected domains of culture and acoustics at the cathedral in the past.

In addition to the scientific aims, the acoustic model of Notre-Dame has been used to draw awareness to the cultural significance of the aural history of the cathedral. This includes a virtual 'magic carpet' tour of the cathedral while listening to an extract from a performance of Massenet's oratorio *La Vierge*. The intention of this production (entitled 'Ghost Orchestra'[2]) was to capture the acoustics of the cathedral and how they vary according to the position of the sound source and the listener. An extended version, offering the entire concert from several fixed positions, was produced during the COVID lockdown in the form of a virtual sound-only experience[3].

The selected piece of music, actually performed at Notre-Dame for its 850th anniversary, offers a unique experience with musicians positioned both in the transept and in the liturgical choir, in addition to several movements where soloists are positioned high up in the galleries, offering spatially variable sources and a truly immersive experience. These efforts have produced a short series of audio dramas, placing the efforts of the scientific team in an easily accessible format. *Looking for Notre-Dame*[4] plunges us into the mind of the young Victor Hugo as he begins work on his future 'cathedral novel' *Notre-Dame de Paris*. Another public work, is the production of a geolocalised audio-guide, *Whispers of the Past at Notre-Dame*[5] , an immersive experience in the aural memories of the cathedral Notre-Dame de Paris. P82

Footnotes

2. **http://www.lam.jussieu.fr/Projets/GhostOrchestra**
3. **http://lavierge2020.pasthasears.eu**
4. **http://lookingfornotredame.pasthasears.eu**
5. **https://youtu.be/i8AE-u9JIU0**

Concluding remarks

Exploring acoustic cultural heritage through digital reconstruction brings an additional perspective and tool-set to researchers in the arts and humanities. Furthermore, it brings a powerful means of communicating and delivering memorable, meaningful and, most importantly, informed multi-sensory experiences. This is evident by the range of projects of this type across Europe. Despite its potential, auralisation is a static representation of how an environment sounds, a snapshot in time, and the final result depends greatly on the limitations of the systems and techniques used to create it. When developing a model of any heritage space, the auralisation is only as good as the groundwork research into the source material documenting its history. Perhaps most importantly, our judgements on the auralisation reflect our selves, our experiences, and our expectations. As with many historical conceptualisations, the final results are created from and perceived through our modern state of mind. Despite these caveats, we believe that Notre-Dame is the perfect opportunity to showcase the opportunities of interdisciplinary partnerships. It is our hope that this work contributes to an appreciation of the cathedral's legacy as it moves towards full restoration.

Acknowledgements

The authors would like to thank the various researchers who have contributed to the measurements and acoustic modelling of the cathedral over the years: Bart N.J. Postma, Julie Meyer, Antoine Weber, and Michelle Castellengo. Funding has been provided by the European Union's Joint Programming Initiative on Cultural Heritage project PHE (The Past Has Ears, **phe.pasthasears.eu**), the French project PHEND (The Past Has Ears at Notre-Dame, Grant No. ANR-20-CE38-0014, **phend.pasthasears.eu**), and the Chantier Scientifique CNRS/MC Notre-Dame. ◎

References

J. Barbier, D. Busson, and V. Soulay. Avant la cathédrale gothique: IVe-XIIe siècle. In Notre Dame de Paris, La Grâce d'une Cathédrale, pages 17–27. La Nuée Bleue, Strasbourg, 2019. ISBN 978-2-8099-0798-8.

E. K. Canfield-Dafilou, S. Mullins, and B. F. G. Katz. Opening the Lateral Chapels and the Acoustics of Notre-Dame de Paris: 1225–1320. n Proc Symp Ancient Theatres, page 5, Verona, Italy, July 2022.

E. K. Canfield-Dafilou, S. S. Mullins, and B. F. G. Katz. Can you hear the paintings? The effect of votive offerings on the acoustics of Notre-Dame. In Proc Forum Acousticum, 2023.

E. Cirillo and F. Martellotta. Sound propagation and energy relations in churches. J Acoust Soc Am, 118(1), July 2005. ISSN 0001-4966. doi:10.1121/1.1929231.

A. Farina. Simultaneous measurement of impulse response and distortion with a swept-sine technique. In Proc AES con 108, 2000.

L. Hamayon. Comprendre simplement l'acoustique des bâtiments [Simply understanding building acoustics]. Le Moniteur, 1996.

J. Hubert. Les origines de Notre-Dame de Paris. Revue d'histoire de l'Église de France, tome 50, n°147, 1964., 1964. ISSN 0048-7988. doi:10.3406/rhef.1964.1726.

B. F. G. Katz and A. Weber. An acoustic survey of the Cathédrale Notre-Dame de Paris before and after the fire of 2019. Acoustics, 2(4):791–802, Nov. 2020. doi:10.3390/acoustics2040044. SI: Historical Acoustics.

P. Luizard and B. F. Katz. Investigation of the effective aperture area of sliding and hinged doors between coupled spaces. J Acoust Soc Am, 136(2):EL135–EL141, 2014. doi:10.1121/1.4890202.

P. Luizard, B. F. Katz, and C. Guastavino. Perceptual thresholds for realistic double-slope decay reverberation in large coupled spaces. J Acoust Soc Am, 137(75):75–84, 2015. doi:10.1121/1.4904515.

D. Mercier. Le livre des techniques du son [The book of sound techniques]. Dunod, 4 edition, 2002.

S. Mullins, E. K. Canfield-Dafilou, and B. F. G. Katz. The Development of the Early Acoustics of the Chancel in Notre-Dame de Paris: 1160–1230. In Proc Symp Ancient Theatres, page 5, Verona, Italy, July 2022.

B. Postma and B. F. Katz. Acoustics of Notre-Dame Cathedral de Paris. In Intl Cong Acoust, pages 0269:1–10, 2016a.

B. N. Postma and B. F. Katz. Perceptive and objective evaluation of calibrated room acoustic simulation auralizations. J Acoust Soc Am, 140(6):4326–4337, Dec. 2016b. doi:10.1121/1.4971422

J. Pätynen, B. F. G. Katz, and T. Lokki. Investigations on the balloon as an impulse source. J Acoust Soc Am, 129(1):EL27–EL33, 2011. doi:10.1121/1.3518780.

D. Sandron. Notre-Dame de Paris: histoire et archéologie d'une cathédrale, XIIe-XIVe si`ecle. L'esprit des lieux. CNRS éditions, Paris, 2021. ISBN 978-2-271-12234-6.

A. Weber and B. F. G. Katz. Numerical simulation round robin of a coupled volume case as compared to scale model measurements. In Intl Cong Acoustics, pages 6051–6058, 2019. doi:10.18154/RWTH-CONV-239933

Glossary

All industries have their own technical terms or abbreviations that don't immediately make sense to lay people. This glossary will help to de-mystify some common terms used in acoustics

<: Less than

>: More than

Acoustic indicator – a series of agreed metrics for describing or measuring sound.

Acoustic narrative – the perception of sound and how that might tell a story of a location.

Amplitude modulation – amplitude (the maximum extent of a vibration or oscillation) varying over time.

Anthropocene — the current geological age, viewed as the period during which human activity has been the dominant influence on climate and the environment.

Attenuator – device used to reduce the strength of an audio signal.

Auralisation – a simulation of an acoustic phenomena.

Binaural measurements – a sound is recorded using two microphones mimicking the placement of human ears (often using a dummy head).

dB – decibel – a unit based on a logarithmic scale used to measure the intensity of a sound.

Hyperacusis – intolerance to common sounds that causes significant distress.

Life Cycle Assessment – (or LCA) a framework for assessing the environmental impacts of product systems and decisions.

Mechanical ventilation – the use of powered fans to provide fresh air to rooms.

Meta analysis – the objective examination of published information to determine overall trends.

Misophonia – a condition where a person has a severe sensitivity to specific sounds and visual images.

Net zero – the target of completely negating the amount of greenhouse gases produced by human activity.

Noise distraction – noise that redirects a listener's attention.

Noise rating (NR) – often used in the measurement of noise from mechanical sources such as air conditioning systems in environments such hotels, cinemas and schools.

Pre-completion testing – pre-completion sound testing places the responsibility for testing on the owner or builder to prove that the sound rating is accurate and complies with modern regulations regarding noise control.

Psycho-social – the psychological development of the individual in relation to his or her social environment.

Reverberation – the reflections of sound that cause a continuation of audible sound beyond an initial event.

Robust detail – a robust detail (RD) is a separating wall or floor construction which has been assessed and approved by Robust Details Limited. In order to be approved, each robust detail (RD) must be capable of consistently exceeding the relevant regulatory performance standards and be practical to build on site).

Sound transmission – how sound energy is transferred from one material to another.

Soundscape – the acoustic environment as perceived by humans, in context.

Soundwalk – a walk that focuses on hearing and listening to the environment. Often linked with soundscape.

Spectrum adaptation terms – the value (in decibels) to be added to the single-number quantity to take account of the unweighted impact sound level, thereby representing the characteristics of typical walking noise spectra.

Speech Transmission Index – a measure of speech transmission quality.

Virtualisation – to produce a virtual version of a real object or sound.

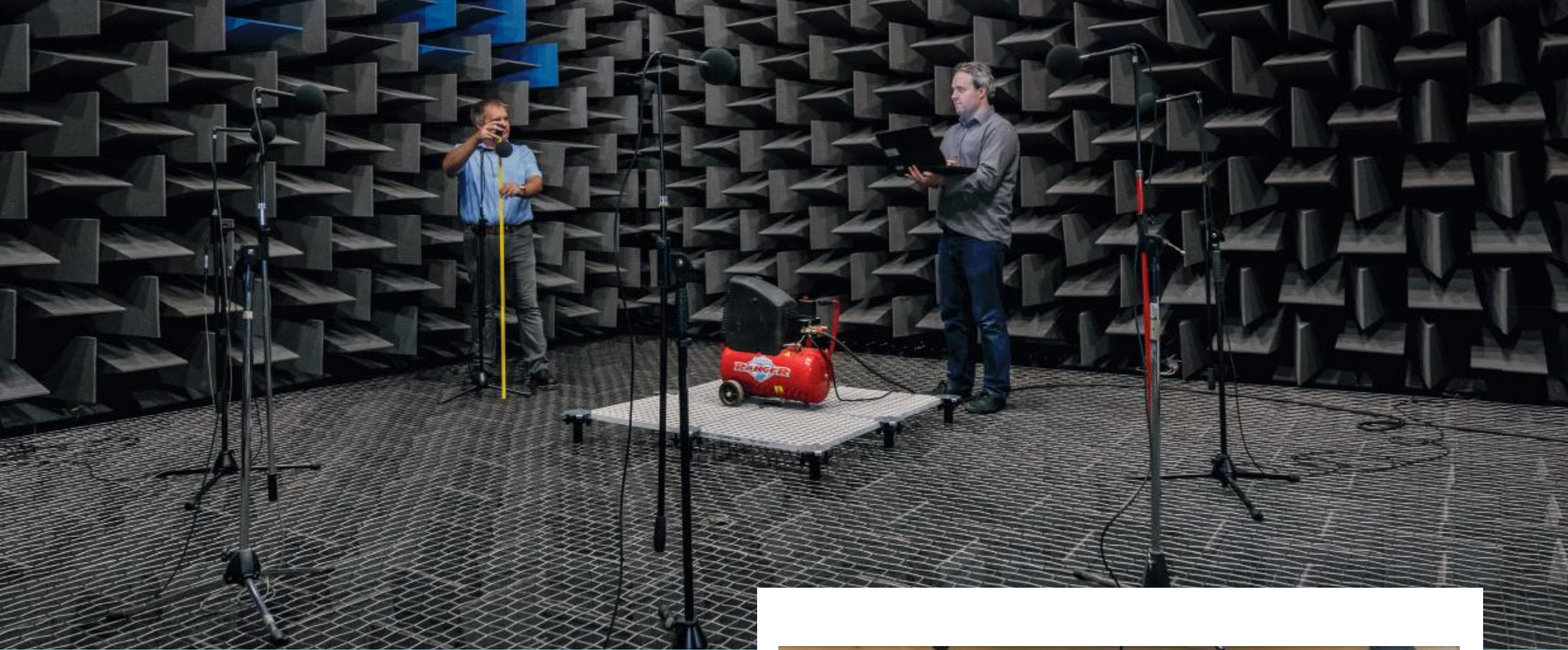
Courtesy of Luis Gomez-Agustina

University of Southampton

ISVR consulting | noise & vibration specialists

Acoustic design and testing for the real world

SPECIALISTS IN NOISE AND VIBRATION SINCE 1968



Our services include:

- Groundborne noise and vibration predictions
- Design of low-vibration buildings
- Acoustic testing of materials and products
- Numerical modelling for noise and vibration
- And more

Click the video above for an introduction to ISVR Consulting

Find out more:
www.isvr.co.uk

Contact us:
consultancy@isvr.co.uk