PROCEEDINGS of the
International Symposium on Room Acoustics

15 to 17 September 2019 in Amsterdam, Netherlands

Acoustic Design of Large Rehearsal Spaces

Paul ADAMS[1], Tom BRICKHILL[1], Ned CROWE[1], Ian KNOWLES[1]; Tateo NAKAJIMA[1]; Bareld NICOLAI[1], Napat WIRIYASUBPACHAI[1], Philip WRIGHT[1]

[1] Arup, United Kingdom

ABSTRACT

Arup's experience in large rehearsal room design is reviewed in the context of platform conditions, musician preferences, and control of loudness. The latter is an ever more critical issue as prevention of occupational hearing loss should become a widely accepted imperative throughout the music industry. To achieve conventional levels of reverberance the implication is that rehearsal spaces become very large, especially in the case of orchestral rehearsal facilities. This naturally presents an economical and practical issue for many organizations. Conventional acoustic design essentially ties loudness, room volume and reverberance together, but electroacoustic systems offer a means of undoing this knot, and enabling control of loudness with reverberance. This points to a means by which musically appropriate rehearsal conditions might be achieved in future without recourse to large volumes.

Keywords: Rehearsal, Noise Exposure, Electroacoustic

1. INTRODUCTION

Over the last twenty years or so, Arup has designed a large number of music practice and rehearsal facilities. This paper reflects in particular on some larger examples primarily intended for orchestral or large ensemble rehearsal, in the context of experiences gained, principles and factors which have guided or emerged through their design and operational life, and likely future direction.

During the course of this period, much research has been carried out on conditions for performers, and related acoustic parameters that help in understanding aspects of the platform environment. And so it is fair to say that aspects of performer conditions are better understood now, although our experience suggests that many aspects of the acoustic environment subjectively apparent to performers are not revealed by contemporary objective measures. Equally there is now an ever increasing awareness and imperative to address noise exposure and the related risk of hearing damage for musicians, through design as well as operational measures.

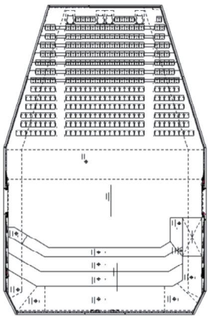
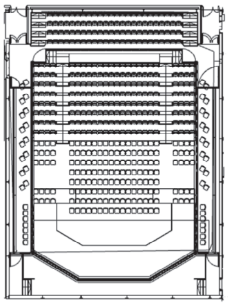
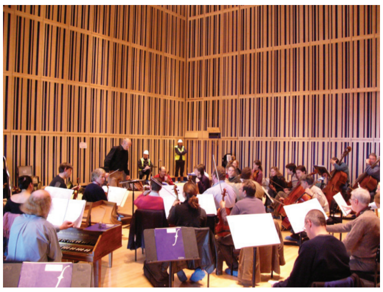
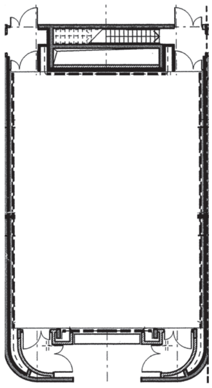
This paper, through examples of completed projects and projects currently in progress, considers the factors that most influence the design of orchestral rehearsal spaces, the way in which acoustic aspects are commonly addressed, and observations from the musicians that help to establish key principles for successful outcomes. Historical design has almost exclusively employed passive acoustic elements, but the principles that emerge for successful design, economic constraints, concern over noise exposure and technological advances, suggest that electroacoustic elements should increasingly be regarded as a natural dimension of the best facilities in future.

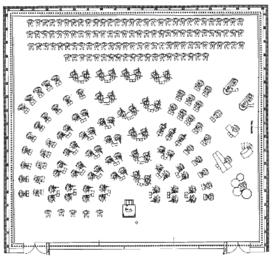
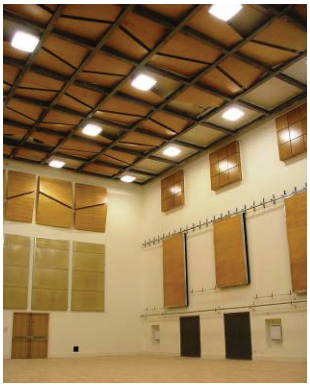
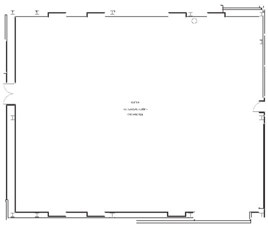
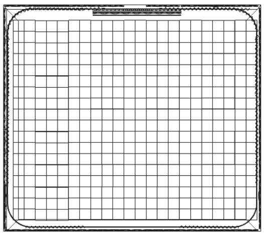
2. PROJECT EXAMPLES

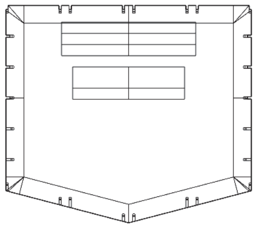
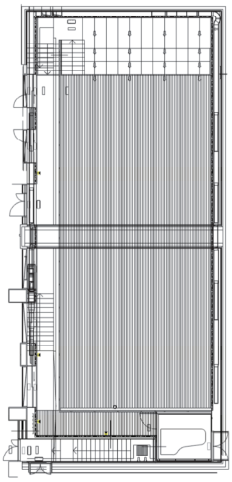
A brief summary of relevant Arup projects is given below, divided into two categories of large rehearsal / studio / performance spaces for symphony orchestras, and smaller orchestral rehearsal facilities within a performance venue complex. Although many common principles apply to these two categories, there is typically a difference in overall size.

[1]philip.wright@arup.com

Table 1: Reference Rehearsal Facilities

Reference	Wire frame with dimensions (L;W;H)	RT range	10log Sα-6	Notable features	Completed
Dedicated rehearsal /performance					
BBC Hoddinott Hall, Cardiff 	36 × 21 × 14 m 	1.6 – 2.0 s	23 dB	Reflector array. Large areas of variable broadband absorption installed.	2009
RSNO Centre, Glasgow 	30 × 13.9 × 13 m 	1.0 – 1.8 s	21 dB	Reflector array. Also used for public chamber performance . Side balconies fold back for orchestral rehearsal	2015
Sage Gateshead, Northern Rock Foundation Hall  (Sinfonia rehearsal)	13m x 17 m x 10 m 	1-1.2	19 dB	Acoustic drapes deployable on all 4 walls	2007

Opera complex rehearsal					
Copenhagen Opera House 	21.5 × 20 × 9.2 m 	1.2 s	21 dB		2004
Wales Millennium Centre, Cardiff 	16 × 20 × 10 m 	1.2 – 1.3 s	20 dB	Sliding absorbent panelling	2004
Stavros Niarchos Foundation Cultural Centre, Athens 	19 × 22 × 12 m 	0.9 – 1.2 s	22 dB	No reflector array.	2016
Isola della Musica, Hanoi	20 × 20 × 13 m	1.0-1.5 s	22 dB	Adjustable reflector array.	In design

Refurbishment projects					
Fiocco Room, Theatre de La Monnaie 	19.5 × 22 × 12 m 	1.6 s	21 dB	Reflector array designed and include curved paneling to the walls under the first balcony	2001
Gulbenkian Grande, Lisbon 	10.7 × 21 × 7.5 m 	0.7 – 0.9 s	19 dB	Electroacoustic system designed but not installed	2014

3. ACOUSTICAL ASSESSMENT OF PLATFORM CONDITIONS

Historically in room acoustics for performing spaces the main focus has been on the acoustics perceived by the audience. In the late 1970’s the first scientific paper by Marshall et al. (1) was published in which objective research on stage acoustics was mentioned.

Nowadays, the most commonly used objective stage acoustic measures are the Support (ST_{early} and ST_{late}) parameters, invented by Gade, proceeding from laboratory (2) and field measurements (3). Since 1997 the ST_{early} and ST_{late} parameters have been included in Annex C of the ISO 3382-1 ‘Measurement of room acoustic parameters’ standard (4).

ST describes the ratio between respectively the early and late reflected energy to the direct energy, for a source-receiver (S-R) distance of 1 m, which is an assumption for the distance between a musicians’ ear (omnidirectional microphone) and his own instrument (omnidirectional source). ST_{early} describes the “ease of hearing other members of an orchestra” (ISO 3382-1), which has to be measured at a fixed 1m S-R distance and may therefore not describe the full picture. Arup commonly computes objective support measures during the design process using computer modelling, and as a means of refining reflector array designs.

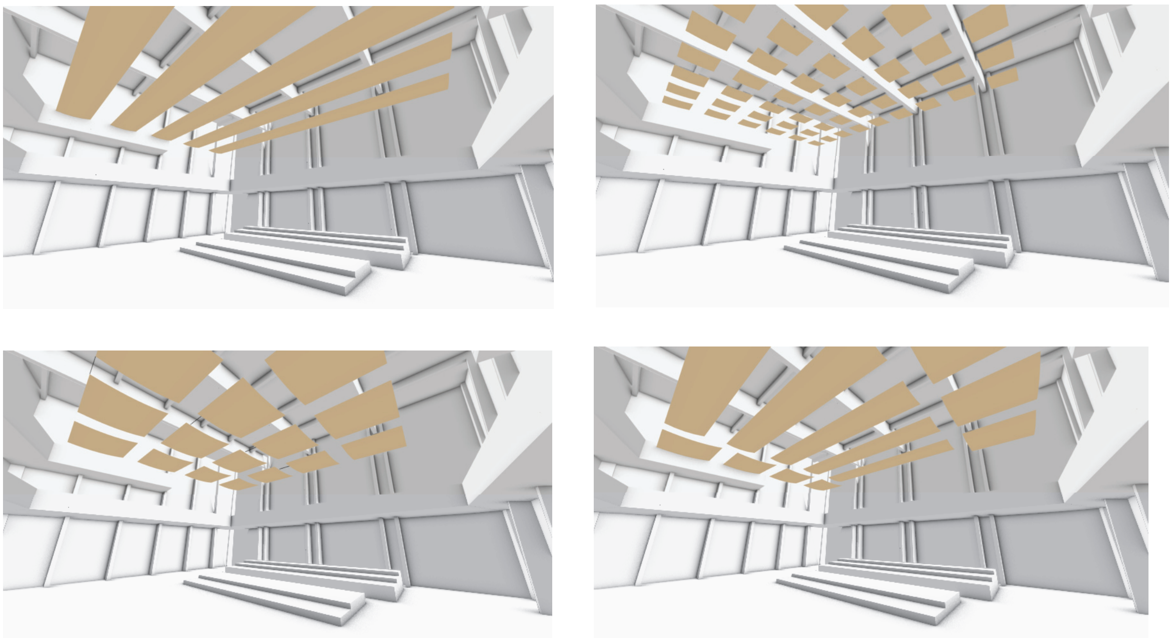


Figure 1: Reflector array options for Fiocco Room, Theatre de La Monnaie

Optimised and extended parameters $ST_{early,d}$ and $ST_{late,d}$ were proposed by Wenmaekers et. al (5) using a variable time interval, which allow measurement of early and late support for various S-R combinations on platforms. Extensive measurements on various platforms showed a clear trend with logarithmic decay for $ST_{early,d}$ as a function of distance, whereas the late sound energy $ST_{late,d}$ is generally not affected by S-R distance (5). Similar trends were found in recent Arup measurement studies, e.g. the graph below shows the $ST_{early,d}$ as a function of distance measured in an orchestral broadcast studio in unoccupied condition.

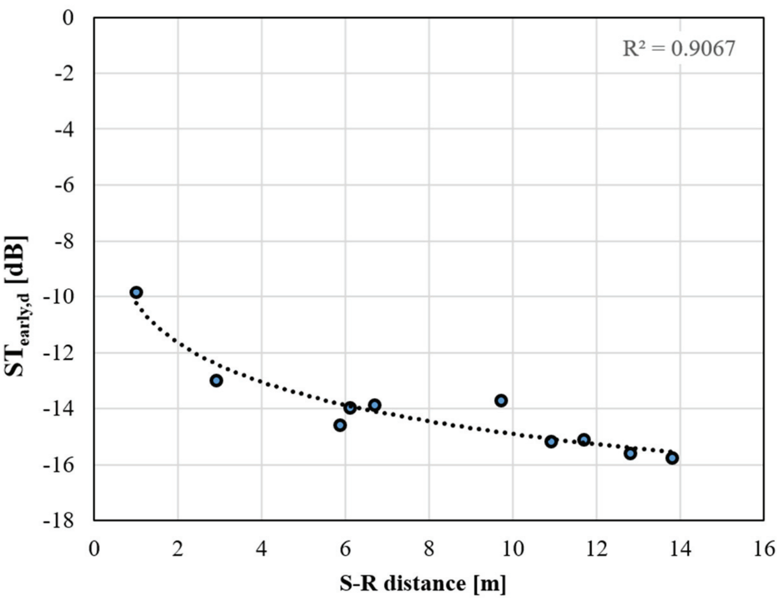


Figure 2: Individual data point for $ST_{early,d}$ as a function of S-R distance. Dashed line represents the logarithmic trend line.

Measurements conducted on occupied versus empty platforms show that the objective stage acoustic parameters are strongly affected by the presence of the orchestra members (6, 7). Modern measurement techniques and careful planning allow conducting occupied platform measurements, however, from experience these are still considered challenging to arrange from a logistic point of view.

Whilst designing future spaces for performance, the challenge remains in simulating and predicting the complex sound propagation on stages taking into account the sound absorption, scattering and reflections from the orchestra. Moreover, there is a missing link between the musicians' subjective experience of ensemble conditions at various distances and preferred objective acoustic target values. It is likely that spatial aspects such as instrument and human hearing directivity play an important role in the sound perception that are not sufficiently accounted for in the current acoustic parameters.

4. DESIGN PRINCIPLES

4.1 Musicians' Preferences

The starting point naturally is an understanding of those fundamental principles which will enable musicians to rehearse effectively and in comfort. Our experience working with musicians is reasonably consistent with much of the literature on surveys of musicians, for example the recent study by Panton (8).

A fundamental requirement is for each musician to hear themselves and their instrument at the right level in relation to others. Their own sound level must be sufficient in relation to others' that they are able to play with good intonation and harmonic sense, but if it is too high relative to others' their timing suffers. On the other hand, if others are too loud their timing is good but their own intonation suffers. They should not only hear themselves at the right level, but the tonal quality of their own instrument should be natural in order for them to achieve good tone production, variation in colour and musical detail.

From the rehearsal space a clear sense of reverberance is also desirable, although any saturation, or an over-loud environment, is very unwelcome, and a wide dynamic range is important.

A degree of support from nearby surfaces is preferred, although percussion sections in particular like to have space to the rear wall.

Time delays (such as perceived delay from woodwind over strings) are highly problematical and early reflection surfaces must be provided which avoid this.

4.1.1 Noise Exposure of Musicians

The control of sound levels for the safety and wellbeing of the musicians should always be considered in the design of any rehearsal space. Since 2008, the UK Control of Noise at Work Regulations 2005 have applied to the music and entertainment sector, placing a responsibility on employers to assess the risk of high sound exposure to their employees and to take action to reduce that risk with hearing protection as a last resort. The regulations, based on the European Directive (2003/10/EC)[9] set limits for daily, weekly and peak sound levels.

Peak sound levels tend to be driven by the distance between players and proximity to sound reflective surfaces (walls, risers and, in the case of orchestra pits, overhangs). UK guidance[10] recommends at least 1.7m^2 per person with 2m^2 per person better, with 2m between the percussion and instruments in front. Even with appropriate spacing, the direct peak levels from a player's own instrument can be very high.

The reverberant level in a rehearsal space has a significant influence on the sound level exposure to the players of an orchestra for a given intensity of playing. However, the design considerations are more complex than simply providing appropriate control of reverberant level. The intensity of orchestral playing is intrinsically linked to the room acoustics of the space, as the players respond to their environment. A study of a pit orchestra conducted by Arup demonstrated that the same orchestra playing the same repertoire can generate sound levels which vary by up to 6dB at a given desk between different venues.

Some of this variation is caused by changes in layout, but orchestral players consistently attest to the need to play more loudly in certain facilities. For example, spaces felt to be lacking in reverberance, even if large in volume, can cause the orchestra to play loudly as it works to 'fill the room'. Even though the reverberant level may not be high, the direct sound between players is increased as a result of their response to the room. Equally, spaces considered to have too much reverberance in comparison with early sound can also result in players playing loudly as they struggle to hear themselves. An essential starting point is to provide a space with an appropriate reverberance so that the orchestra does not over-play. The space should then have an appropriately controlled reverberant level. For a given room volume, the reverberant level and reverberance are highly correlated, so striking the right balance can be a challenge – especially where there are geometric site restrictions imposed on the design.

4.2 Plan Dimensions

Plan dimensions generally arise from layout requirements of the ensemble in question – with room around the sides for circulation and set-back of wall reflections. So a typical plan area for symphony rehearsal might start at about 18 x 13 m, which for circulation and space at the rear might increase to 22m x 17m. Many of the rehearsal/broadcast studios include a small area for audience (typically 300 – 500 seats) which has the double benefit of increasing the plan area (and hence volume) of the room and also increasing the absorption thereby reducing the reverberant level.

Because of the desire to separate musicians during rehearsals for Noise at Work considerations (especially between brass and surrounding sections) a typical platform layout for performance may be more compact than that for a full day rehearsal. The trade-off between the artistic and musical benefit of the orchestra being as compact as possible and sound exposure levels is one that many orchestras are grappling with at the moment.

This is apparent when reviewing several relatively new orchestral rehearsal/broadcast studios, whereby the very expensive mechanized riser installations that were appropriate at the time of the design of the facility no longer serve the needs of the orchestra, given the spread of orchestras over the last 10 years or so. This means that additional manual risers are needed to supplement the mechanized stage risers. There are also examples of orchestral reflector arrays that no longer extend across the length of the orchestra as the area of the orchestra has changed. Going forward it is important that maximum flexibility for performer locations within any given space is considered from the outset of the design process.

4.3 Height, Reverberance, Loudness

While plan dimensional requirements are commonly well defined by a combination of ensemble and audience space requirements, a number of factors are considered in relation to height.

1. Generally, no matter what the plan dimensions, a ceiling height of less than 10m is considered too low, owing to the risk of saturation and over-loudness.
2. Arup review of historical rooms concluded some time ago that a bare minimum 21dB (10lgSα-6) was required to control loudness in occupied condition for full orchestra. This figure is adjusted according to the size of the ensemble, for example 22dB for orchestra plus choir; 20dB for sectional rehearsal. This is factored into height requirements, although would not normally drive height in larger facilities.
3. Range of reverberance – this can vary according to client / orchestra demands, but it generally imposes a minimum height requirement in order to achieve the RT range within the context of the minimum (eg 21dB absorption) loudness limit. This is normally tested for a range of potential ensemble sizes. In Arup's experience the RT is never higher than 1.5-1.6s, because otherwise the increase in reverberant level leads to saturation.
4. These considerations imply a variable acoustic system is an essential component, to achieve variation in both reverberance and loudness.

Within the context of these considerations, Arup's preference generally is for as much height as possible, and more commonly than not installation of a reflector array system which is as flexible as possible, to allow for variability in layout, and the particular demands of repertoire and conductors.

An example of how reverberance, loudness and variable acoustic elements were considered (for the RSNO Centre) are set out below.

Figure 3: RSNO Centre, Glasgow

Table 2: Initial design values for RSNO Centre

Mode	Occupation	Variable absorption	Parameter	Value / range
Rehearsal (seating and walls / panels retracted)	Full orchestra + chorus	≤ 75%	MF RT	1.2s – 1.6s
			MF EDT	85% - 100% of RT
			LF RT	100% - 120%
			10logSα-6	≥ 22dB
	Full orchestra	≤ 75%	MF RT	1.2s – 1.6s
			MF EDT	85% - 100% of RT
			LF RT	100% - 115%
			10logSα-6	≥ 21dB
	Sectional rehearsal (12)	≤ 80%	MF RT	1.3s – 1.6s
			LF RT	100% - 115%
			MF EDT	85% - 100% of RT
			10logSα-6	≥ 20dB
Performance Rehearsal (seating and walls / panels in place)	Chamber orchestra (30)	≤ 50%	MF RT	1.4s – 1.6s
			LF RT	100% - 120%
	Amplified band (6)	100%	MF RT	< 1.2s
			LF RT	< 1.5s

4.2 Early Reflection Surfaces

While room boundaries are driven to a large extent by considerations of layout and loudness, the quality, intensity and timing of early reflections which they provide are critical.

In addition to the platform itself musicians often express a preference for lateral and rear support, but generally do not want surfaces too close or which they consider provides a colouration. A mildly diffusing surround is normally preferred, with a degree of set back from percussion. On occasions absorptive material is brought close to players, to help control sound levels. This can be counterproductive though, altering tonality and reducing support, and causing players to play more loudly. The variable absorption elements for significant adjustment of RT and loudness are therefore located at mid and upper levels, with a reflecting wall projection or ledge at 4m or so a useful source of additional support.

In almost all spaces additional overhead reflections within 10m or so are normally required in practice for sufficient support and ensemble, and commonly an overhead array is installed. In some cases musicians set arrays as low as 6m when loudness is not critical, although generally a height of 8-10m is more common. Flexibility is therefore key, noting that musicians are quick to notice comb filtering effects from overheard reflections in particular. Therefore arrays of smaller reflectors are often used, often double-curved. Design to ensure overlapping coverage is beneficial to ensure overhead support is effective without causing harshness.

Figure 4: BBC Hoddinott Hall, Cardiff

A limited bass rise is generally preferred, and therefore surfaces around the platform can generally be lighter than would be the case in larger performance venues. As the most cost effective variable acoustic elements are usually banners or drapes, fixed low frequency absorbers are normally employed to ensure bass rise is limited in all conditions. This is not a straightforward aspect of design, partly because of the uncertainty over low frequency absorption (which can be ameliorated somewhat by a series of laboratory tests), and partly because a reasonably flat response can be considered to sound somewhat unnatural in larger facilities. Variable low frequency absorption would be beneficial, but in practice fixed absorbers tend to be installed with the variable elements most effective at mid and higher frequencies.

5. DISCONNECTING LOUDNESS AND REVERBERANCE

In all of the examples above, the normal relationship between reverberant loudness and absorption is established. Within that context overall acoustic volume essentially provides the means for providing reverberance, and since plan area is often established first, height is the means of providing this. While 10m is normally an effective minimum, at least 13m with an array below is a preferred arrangement for a full symphony orchestra.

However Arup's experience suggests that reflector arrays at 8m or so work well (provided this is in a context where loudness issues will not be exacerbated), so acoustically speaking the need for greater height stems above all from the need for reverberance, assuming a sufficient quantity of absorption to control loudness. In building massing and economic terms, such acoustic pressure for height is often extremely problematical.

In fact the umbilical link between reverberance and loudness is a fundamental inconvenience, in design terms. It would arguably be far preferable to be able to consider each independently of the other. Recording engineers of course effectively do this routinely, adding reverberance artificially "to taste" once a satisfactory microphone balance has been achieved. Griesinger (11), notably, has argued that acoustic design can learn from that process, and has elaborated on the interplay of timing, spectrum and level of late (reverberant) sound in subjective judgements of reverberance. In the context of the imperative to reduce noise exposure of musicians, the prospect of being able to control loudness while at the same time achieve a subjectively pleasing sense of reverberance is highly attractive in the context of rehearsal facility design, and naturally points to contemporary electroacoustic and audio processing technology as a means of doing so.

6. ELECTROACOUSTIC ENHANCEMENT

Electroacoustic Enhancement systems, also known as Active Architecture systems, have been available commercially for over 20 years. Although each system uses a different approach, they all aim to achieve a similar outcome, that of being able to alter the perceived acoustic environment of a space through the use of microphones, loudspeakers and some kind of digital signal processing. The potential value in terms of achieving flexibility of conditions to suit a variety of users (asset sweating), and within a reduced volume, is clear. Nevertheless there are a few basic limitations that must be considered:

- The natural RT of a space cannot be made shorter than it is without the system. The natural acoustic is the default state and the system can only add to reverberant field. If the design needs a wide variation of reverberation, then the natural state will need to be reasonably "dead".
- The seamless transition between the natural and artificial reverberant fields becomes less believable the closer the listener is to a loudspeaker. This is because the listener will start to localize the sound coming from the loudspeaker rather than it being part of the reverberant field. This is essential to consider during design to ensure that loudspeakers are located at a reasonable distance from listeners/performers. The rule of thumb is that the closer the listener is to the loudspeakers, the closer together the loudspeakers need to be arrayed. The exact distances are a factor of the loudspeaker directivity.
- When increasing the reverberation of a space though active architecture, there is generally a point where the listener experiences a sense of cognitive dissonance where the visually perceived size of the room no longer matches the acoustically perceived size. Unless this is being used for dramatic effect, the experience for the listener can be quite off putting. This psychological factor is important to consider because even though the generated acoustic environment might be an appropriate artistic choice with relation to the music, the users may find the space uncomfortable. This means that when determining the size of an orchestral rehearsal space, a designer must consider not just the actual acoustic characteristics of the space, but also the perceived or "naturally anticipated" acoustic characteristics. Overlaid upon this consideration is a degree of cultural resistance within the classical music industry to non-acoustic or artificial elements. For both of these reasons there is clearly a delicate balance to be struck with overall room size and the extent of and perceived magnitude of any electroacoustic intervention.
- If the natural acoustic parameters of the room are not "good", the system will not necessarily make it better. In other words, if the room has acoustic artifacts like flutter echoes or strong modes, the system is likely to exacerbate these, not fix them.

In additional to being able to adjust the reverberation time of a space, an Active Architecture system can allow the users to adjust the tonality and timbre of the artificial reverberant field. This presents the opportunity for the performers to explore the relationship between performance and space in a dynamic way that generate new ways of presenting sonic experiences. This kind of experimentation has been apparent in work by the San Francisco Symphony Orchestra at the SoundBox venue in San Francisco. Active Architecture systems have also featured quite prominently in work produced by Cirque du Soleil for many years.

The use of Active Architecture over spatial audio reproduction systems is an important distinction to make. Spatial audio reproduction systems (i.e. wavefield synthesis, higher order ambisonics, vector-based amplitude panning etc.) differ in that they don't generally involve a live input from the reverberant field. The two systems can work in combination, however the Active Architecture system is distinct in that it specifically aims to capture the live acoustic environment and enhance it, rather than playback discreet spatialised content. In the live performance context, this can allow the operator to enhance naturally occurring sounds (eg. audience applause) for dramatic effect.

The design and supply of these systems has historically been the domain of specialist suppliers. The nature of these organisations varies from large manufacturers to smaller researchers and technologists. The way in which a system is conceived, designed, installed and integrated varies between suppliers. Because of this, the role of the consultant in the procurement of these systems is important to ensure that the users end up with a system that is integrated with the room acoustics, appropriate to their performance uses and operations.

The introduction of an Active Architecture system into an orchestral rehearsal space may present an opportunity to design a room with a ceiling height lower than accepted minimum of 10m. A ceiling reflector array would need to be carefully designed to integrate sufficient absorption, diffusion and loudspeakers to ensure that loudness could be adequately controlled and the knitting together of natural reflections and artificial is as seamless as possible. An example of this is shown in Fig 5.

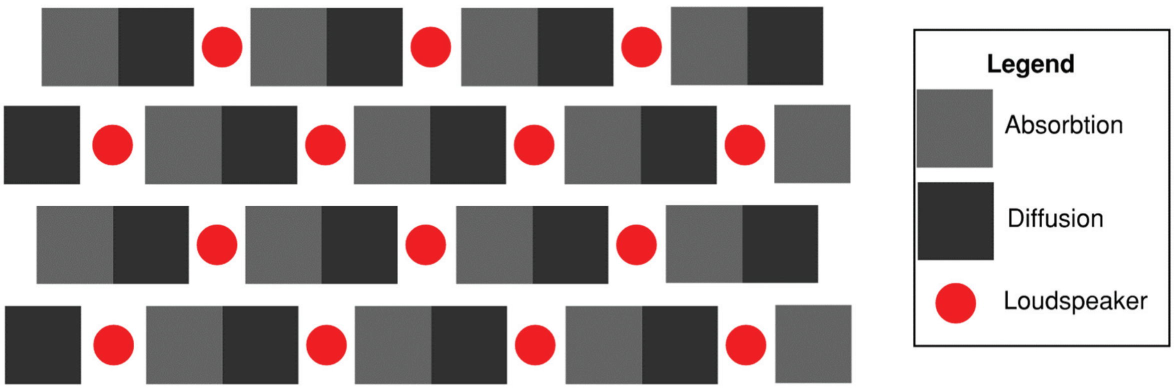


Figure 5: Potential reflector layout

There are also a number of practical considerations to be taken into account when investigating the use of an electroacoustic enhancement system. One is the views of the musicians that will be using the space – many musicians are initially reluctant to rely on the use of an electronic system to provide an acoustic experience that is traditionally entirely passive, particularly for instruments that themselves are passive. This can be overcome to some extent by involving the musicians in the design process and allowing them to visit, listen to and experiment with different systems.

Another consideration is the process of procuring the systems. Some organisations, particularly public ones, will require a tender process that considers more than one supplier. The systems on the market are quite different in terms of both the base room acoustic conditions needed and the required number and locations of loudspeakers and microphones. This presents challenges in terms of designing a room that is capable of providing an appropriate base acoustic and integrating a number of different systems before the final supplier is known.

7. FINAL REMARKS

The creation of productive, comfortable working conditions has naturally always been a priority in the design of larger rehearsal facilities, and partly owing to the growing awareness of the need to reduce sound exposure levels of musicians, there has been a trend – as seen for example in facilities designed for use by BBC orchestras in the UK – for larger facilities, with obvious implications for cost and viability. While there are many subtleties to the acoustic environment around an orchestra which contemporary objective measures do not yet fully describe, it is clear that the primary acoustic association between reverberance and loudness has driven critical elements of design in practice. Looking forward, although there are procurement, connected-design and cultural issues to overcome, Arup's perspective is that electroacoustic (active architecture) systems offer intriguing possibilities for creating less space-demanding facilities with a convincing, independently tunable reverberance at the same time as optimised early reflections and well-controlled loudness.

8. REFERENCES

1. Marshall, A. H., Gottlob, D., & Alrutz, H. (1978). Acoustical conditions preferred for ensemble. The Journal of the Acoustical Society of America, 64(5), 1437-1442.
2. Gade, A. C. (1989). Investigations of musicians' room acoustic conditions in concert halls, part I: Methods and laboratory experiments. Acta Acustica United with Acustica, 69(5), 193-203.
3. Gade, A. C. (1989). Investigations of musicians' room acoustic conditions in concert halls. II. Field experiments and synthesis of results. Acustica, 69(6), 249-262
4. ISO 3382-1:2009 - acoustics - measurement of room acoustic parameters - part 1: Performance spaces. International Organisation for Standardisation, Geneva, Switzerland.
5. Wenmaekers, R. H. C., Hak, C. C. J. M., & van Luxemburg, L. C. J. (2012). On measurements of stage acoustic parameters: Time interval limits and various Source–Receiver distances. Acta Acustica United with Acustica, 98(5), 776-789.
6. Wenmaekers, R. H. C., Hak, C. C. J. M., & Hornikx, L. C. J. (2016). How orchestra members influence stage acoustic parameters on five different concert hall stages and orchestra pits. The Journal of the Acoustical Society of America, 140(6), 4437-4448.
7. Dammerud J. J. & M. Barron (2010). Attenuation of direct sound and the contributions of early reflections within symphony orchestras. The Journal of the Acoustical Society of America, 128, 1755-1765
8. Panton, L. (2017). Investigating auditorium acoustics from the perspective of musicians, University of Tasmania, PhD thesis.
9. European Parliament and Council, Directive 2003/10/EC of the European Parliament and of the Council of 6 February 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise), Official Journal of the European Union, (2003)
10. Sound Advice: Control of noise at Work in music and entertainment, the Health and Safety Executive (2008)
11. Griesinger, D. How loud is my reverberation? In Proc. of 98th Audio Engineering Society Convention, Paris, France, 1995. Audio Engineering Society