The purpose of this report is to review the literature on sound distribution in entertainment venues as it pertains to safe-listening practices. The document was prepared by Dr Ian M Wiggins from the National Institute for Health Research Nottingham Biomedical Research Centre, UK and Ken Liston from the Nottingham Trent University, Confetti Institute of Creative Technologies, UK.
Sound distribution for safe listening in entertainment venues: a review

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<td>Audio Engineering Society</td>
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<td>dB</td>
<td>Decibel</td>
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<td>DSP</td>
<td>Digital signal processing</td>
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<td>FOH</td>
<td>Front of house</td>
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<td>High frequency</td>
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<td>In-ear monitoring</td>
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Purpose of this report

The purpose of this report is to review the literature on sound distribution in entertainment venues as it pertains to safe-listening practices; that is, the enjoyment of amplified sound without endangerment to hearing health. The report was put together at the request of the Ear and Hearing Care team at the World Health Organization (WHO), to inform the development of a regulatory framework for control of sound exposure in recreational settings.

It is the authors’ understanding that the WHO has simultaneously commissioned reports on related issues, including appropriate limits for sound exposure in recreational venues, public health messaging, and provision of hearing protection. It has been the aim of the authors to ensure that the present report will complement, while minimally duplicating, the content of these other reports.

An important aspect of sound distribution in entertainment venues is the effective control of sound spillage to neighbouring properties. Such spillage is often the subject of local regulations, designed to protect neighbours from noise pollution. This can be a problem especially at outdoor events. However, the issue in such cases is almost invariably one of annoyance, rather than of risk to hearing health. As such, the issue falls outside the scope of the present report and is not considered further.
Executive summary

In the context of safe listening, sound distribution has two key (and interrelated) aspects: (1) the design of the electroacoustic sound reinforcement system (the “public address” (PA) system); and (2) the way that sound propagates throughout the venue (“venue acoustics”). This report addresses both aspects.

It is important to note that the risk of sound-induced hearing injury is ultimately determined by the sound pressure level (SPL) at a listener’s eardrums, combined with the duration of the exposure. Sound distribution cannot affect “what is safe” in this respect. Sound distribution does, however, play a key role in determining whether safe listening conditions will be achieved for all members of an audience, or for some, but not others. Good sound distribution may also be a pre-requisite to be able to comply with safe-listening regulations in practice.

At present, there is very little scientific literature directly addressing the impact of sound distribution on the risk of hearing injury due to recreational sound exposure. We therefore review publications on related topics, using our own knowledge and reasoning to relate the findings to a safe-listening context as appropriate.

The report is structured as follows:

In PART I, we introduce the topic and discuss what sound distribution should look like in a “safe-listening venue.” We also explore how sub-optimal sound distribution (especially venue acoustics) might hamper efforts to achieve safe-listening conditions in practice.

In PART II, we assess the current state of affairs. We review the evidence-base on sound distribution in entertainment venues in the context of existing “safe-listening” policies and regulations from around the world. We critically review requirements of such policies and regulations that relate to sound distribution, drawing on peer-reviewed literature, theory and calculation to assess their expected effectiveness.

In PART III, we explore relevant issues in room-acoustic and electroacoustic design in greater depth, identifying advice on how the goal of delivering high-quality and impactful sound in entertainment venues, while at the same time protecting the hearing of audience members, can be achieved.

The main conclusions of the report are:

- A suitable design goal for a “safe-listening venue” would be to achieve, as far as is practicable, uniform sound levels throughout the audience area. This is also one of the main quality criteria for modern sound-system design, so “safe listening” and “sound quality” go hand-in-hand.

- Although a uniform sound distribution is generally desirable, venues should not be penalized for deliberately targeting lower sound levels in certain areas, for example, in bar or lounge

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1 The implementation of regulations designed to protect the hearing of audience members will invariably involve a trade-off between the desire to minimize health risk on the one hand and the desire to support artistic freedom and the continued enjoyment of loud amplified music on the other. Since some individuals will attend venues and events featuring amplified music more often than others, there is little control over cumulative long-term exposure. For this reason, while in the present report we generally refer to “safe listening,” strictly speaking, “softer listening” may be the more accurate term.
areas, or towards the rear of a performance space. This can improve patron choice and comfort. The key consideration is to ensure that hazardous sound levels are avoided at all positions in the venue that are, or could be, occupied by an audience member. This includes directly in front of the main loudspeakers, which usually, though not in all cases, corresponds to the most-exposed location.

- Spatial variation in sound levels throughout existing venues varies widely, from <3 dBA in some venues to >12 dBA in others (and with worst-case values estimated to be >20 dBA). There is some evidence that spatial variation tends to be slightly greater at outdoor events than in indoor venues, consistent with generally larger audience areas and the absence of room reverberation outdoors (in indoor venues, room reverberation tends to have a partially equalizing effect on sound levels throughout the venue).

- Sound levels measured at the front-of-house mixing desk will underestimate those occurring within the audience area to a greater or lesser extent, especially compared to the “most-exposed” audience location. A correction may therefore be needed to front-of-house measurements in order to quantify audience exposure, although further research is needed into the accuracy of such corrections and the conditions under which they are valid.

- Sound levels can be expected to increase rapidly as one approaches a loudspeaker. Regulations designed to maintain a minimum separation between the loudspeakers and the nearest audience members are therefore well motivated. However, purely distance-based criteria (e.g. “no access within one metre of any loudspeaker”) are somewhat arbitrary, since the maximum output capability of different types of loudspeaker commonly used in sound-reinforcement applications can vary by 30 dB or more. It is also important to note that one of the primary draws of live music, especially in smaller venues, is being able to get close up to the performers, which may in some cases unavoidably mean being in close proximity to a loudspeaker.

- Sub-optimal venue acoustics may lead to difficulty complying with sound-level limits. The primary issue is excessive reverberation in venues that feature mostly hard, reflective surfaces. Fortunately, poor acoustics can in many cases be dealt with through the introduction of appropriate acoustic treatment. Published advice is available regarding suitable reverberation time targets for venues designed for amplified music. Adhering to sound-level limits may remain challenging if reverberation cannot readily be controlled, for example, in tented venues, which can have very long mid-frequency reverberation times.

- In smaller indoor venues, recommended sound-level limits may be exceeded purely by sound from on-stage sources, including drum kits, backline amplifiers, and monitor loudspeakers, before the main PA system has even been turned on. Stage spill to the audience area can be reduced by making the stage surroundings acoustically absorbent, in combination where necessary with the use of clear acoustic screens to block direct-sound transmission from particularly loud instruments. However, the most effective solution is to reduce stage levels at source. Measures such as replacing on-stage monitor loudspeakers
with personal in-ear monitoring for the musicians and moving backline amplifiers off-stage (or at least orienting them away from the audience) are recommended where possible.

- Appropriate sound-system design is key to achieving uniform sound distribution. A fundamental principle is to avoid a situation in which some audience members are located much closer to the loudspeakers than others, especially if more distant audience members do not have direct line-of-sight to the loudspeakers. Elevating the loudspeakers above head height and the use of “delay” loudspeakers to support sound delivery to the rear of the audience are recommended where appropriate. Software tools are available to help identify the optimal loudspeaker configuration(s) to achieve uniform coverage in a particular venue. To help the sound engineer deliver a clear and controlled mix in indoor venues, the sound system should be designed to direct sound towards the audience and away from the walls and ceiling.

- In most sound-reinforcement systems, low-frequency sound is reproduced by dedicated “subwoofer” loudspeakers. It remains common practice to place the subwoofers at ground level close to the stage, although research shows that flown subwoofer systems may be capable of achieving more uniform low-frequency coverage from front-to-back of an audience. Especially at large-scale events, the front rows of the audience are often exposed to extremely high levels of low-frequency sound, even when A-weighted sound levels are within recommended limits. Further research is needed to understand the extent to which such intense low-frequency exposures pose a risk to the human auditory system. Flown subwoofers may be impractical in small venues with limited ceiling height and/or rigging capacity.

- There is little published literature directly evaluating whether adoption of the sort of room-acoustic and electroacoustic design principles identified in this report is effective at reducing audience sound exposure. However, a case study from Sweden offers promise that it is possible, through reasonably simple and straightforward steps, to tackle excessive sound exposure even in the challenging case of a small, indoor rock club. Following improvements to the acoustics of the venue and a redesign of the PA system, it was possible to bring sound levels within a government-recommended limit of 100 dB $L_{Aeq}$, whereas prior to the renovation the levels had been closer to 110 dB $L_{Aeq}$. However, technical improvements alone are not sufficient to guarantee a reduction in sound levels; to achieve that requires buy-in from all stakeholders, not least the sound engineer.
PART I: What should sound distribution look like in venues supporting safe-listening practices?

Introduction

Live music is enjoyed by audiences all around the world, delivering significant cultural and economic benefits. Amplified music also features prominently in venues such as bars, clubs and gyms, where the presence of loud music is in many cases an integral and highly valued part of the experience for patrons. However, excessive exposure to amplified sound can result in permanent hearing damage, especially if sound levels are allowed to increase to very high levels unchecked (Petrescu, 2008).

The risk to an individual patron or audience member will depend on the SPL to which they are personally exposed, combined with the duration of the exposure (Daniel, 2007). An important factor therefore is the “sound distribution” within the venue, since this will determine the relative SPL that different audience members are exposed to.

Sound distribution in the context of entertainment venues has two key (and interrelated) aspects: (1) the design of the electroacoustic sound-reinforcement system (the “public address” (PA) system); and (2) the way that sound propagates throughout the venue (“venue acoustics”). The acoustics of a venue are primarily dictated by its size and construction (topography for outdoor venues), although they can be modified through changes to layout, furnishings and surface materials, or remedial architectural work. Typically, a sound-reinforcement system will be designed, installed and operated with a view to achieving the best sound quality possible (in the ears of the designer/operator), given the acoustical characteristics of a particular venue.

Figure 1 shows a schematic for a typical sound-reinforcement system. The concert is mixed by a sound engineer located at the front-of-house (FOH) position. The primary source of sound delivered to the audience is the main loudspeakers, often located to the sides of the stage. These “mains” may be supported by an array of “subwoofers” (in this example lined in front of the stage), which are loudspeakers that specialise in producing only low-frequency, i.e. bass, sound (30–100 Hz).

Typically, there will be multiple sources of sound on stage. As well as individual instruments and “backline” (guitar amplifiers, etc.), there will usually also be “stage monitors”, which are loudspeakers that direct sound towards the musicians to help them hear their own performance. As well as the familiar wedge-shaped floor monitors, some systems also include “side-fills” (monitor loudspeakers positioned upright at the sides of the stage, which are often large and capable of producing very high sound levels). At larger events, the monitor system may be under the control of a dedicated monitor engineer, usually located at the side of the stage. Audience members standing close to the stage will invariably receive a mixture of sound directly from these on-stage sources and via the main PA system, whether or not this is desirable.

An inherent property of sound is that it reduces with distance: in most cases sound obeys the “inverse square law”, which means that for each doubling of distance, the SPL decreases by 6 dB. Because of this reduction in sound level with distance, at larger events additional loudspeakers are sometimes needed to help deliver sound to more distant audience members. These additional

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2 Note that the frequency range reproduced by subwoofer loudspeakers (30–100 Hz) lies more than an octave below the lowest frequency (250 Hz) tested in routine clinical audiometry (e.g. BSA, 2018. Recommended procedure for pure-tone audiometry. British Society of Audiology, Bathgate, UK.)
loudspeakers are known as “delays”, because the signal that is delivered to them is electronically delayed to ensure that their sound arrives synchronously with the sound from the main loudspeakers.

As a consequence of the laws of physics, sound distribution is inherently frequency dependent. Firstly, loudspeakers do not emit sounds in the same way at all frequencies: they tend to be closer to omnidirectional (sound emitted equally in all directions) at low frequencies, and more directional (sound emitted more strongly in some directions than others) at high frequencies (Davis et al., 2013). Secondly, once sound has left the loudspeakers, low-frequency sound tends to travel everywhere, bending around obstacles and reflecting off surfaces, while high-frequency sound is more easily blocked or absorbed (Kuttruff, 2009). The rate at which sound levels fall off with distance can also be frequency dependent, for example in the case of line array systems that are a mainstay of modern sound-system design (see PART III for details).

**Figure 1**  
Schematic showing the main components of a typical sound-reinforcement system (FOH = Front-of-house).

Frequency spectrum of amplified live sound  
Since sound distribution varies with frequency, it is important to consider the frequency spectrum of amplified live sound. The solid blue line in Figure 2 shows the 1/3-octave-band long-term spectrum measured at FOH, averaged across 170 concerts (Støfringsdal, 2018). The dashed and dotted lines show the same spectrum after application of either the A- or C-weighting curve, respectively. Also plotted for reference are the long-term spectrum of recorded popular music, averaged across 12,345 tracks (Elowsson and Friberg, 2017), and a pink-noise test signal. All spectra were normalized to have the same broadband level of 100 dBA.
A number of observations can be made:

1. Low-frequency energy is predominant in live sound (as measured at FOH);
2. As is well known, application of the A-weighting curve emphasizes mid-to-high frequencies (especially around 1–4 kHz), but renders measurements almost completely insensitive to the low-frequency range (below around 200 Hz) where much of the energy exists in live sound;
3. In contrast, the C-weighting curve is effective at capturing the energy of live sound over the full audio bandwidth;
4. Live sound features a pronounced boost of around +10 dB in the subwoofer range (30–100 Hz), which is not present in the average spectrum of recorded popular music (though may be present to some degree in tracks that are more percussive in nature—see Elofsson and Friberg (2017)). This low-frequency boost may at least in part reflect the deliberate tuning of live-sound reinforcement systems to deliver low-end “punch”;
5. The use of pink noise as a test signal to measure broadband sound levels may systematically under-emphasize low frequencies and over-emphasize high frequencies, compared to real musical material. Thus, care is needed when interpreting broadband sound levels measured with a pink-noise source, as such measurements may not be representative of the levels that will occur during a musical performance. (Note: this is not an issue when pink noise is used to measure levels in individual frequency bands, such as one-third-octave bands).

![Figure 2](image-url)  
*Figure 2* Long-term average one-third-octave-band spectra of live sound measured at FOH (plus the effect of A- and C-weighting), recorded popular music, and pink noise. All spectra were normalized to a broadband level of 100 dBA.
It is clear from these observations that A-weighted measurements will capture only a fraction of the overall energy present in amplified live sound (cf. DELTA SenseLab, 2013). As will be shown in PART II, it is possible for some audience members to be exposed to very high levels of low-frequency (30–100 Hz) sound, even when A-weighted levels have been brought under control. Use of the A-weighting curve is embedded in international standards for determining occupational noise exposure and estimating the associated risk of a permanent decline in audiometric thresholds (e.g. International Organization for Standardization, 2009; 2013). The additional risk to hearing posed by exposure to intense low-frequency sound is poorly understood. Although transmission of sound through the outer and middle ear is markedly less efficient at these low frequencies (Puria and Steele, 2010), there are several reasons why caution may be appropriate:

1) Studies in humans have demonstrated that exposure to intense low-frequency (<100 Hz) tones or noises can result in significant temporary threshold shift (TTS) at frequencies in the 1–8 kHz region (Jerger et al., 1966; Patterson et al., 1977). While a TTS may resolve fully, leaving no permanent loss in audiometric sensitivity (Ryan et al., 2016), these results nonetheless show that exposure to intense low-frequency sound can have physiological consequences that extend to higher frequencies.

2) Recent studies in animals have revealed that, contrary to long-held belief, the outer hair cells are not the component of the mammalian inner ear most susceptible to noise damage: instead, it is the synapses connecting inner hair cells to auditory nerve fibres that are most vulnerable (Kujawa and Liberman, 2009). Loss of these synapses, known as “cochlear synaptopathy,” can occur to a severe degree without any elevation of audiometric thresholds; it may, however, result in supra-threshold hearing deficits including difficulty understanding speech in noise, tinnitus and hyperacusis. It is not yet clear to what extent humans are susceptible to this form of neural pathology brought on by exposure to intense sound; however, humans do exhibit pronounced neural loss within the cochlea over the lifespan, presumably due to some combination of aging and noise exposure (Wu et al., 2019). In animal studies, the loss of synapses tends to occur over a broad frequency range, with the maximal loss occurring at a frequency considerably higher than that of the damage-inducing noise stimulus (e.g. Fernandez et al., 2020). Hence it is possible, though currently unproven, that intense low-frequency exposures could accelerate the loss of synapses along the tonotopic axis, including at higher frequencies.

3) Recent histological work examining temporal bones obtained from autopsy material has revealed that, over the human lifespan, pronounced loss (~70%) of outer hair cells occurs at locations within the cochlea tuned to the lowest frequencies (below those assessed in routine audiometric testing) (Wu et al., 2019). Apical loss of outer hair cells has similarly been observed in animal models of age-related hearing loss (Kujawa and Liberman, 2019). In humans, it is unknown to what extent this loss of outer hair cells at the apex of the cochlea might be accelerated by intense low-frequency exposures of the type experienced in entertainment venues.

Further research is needed to understand the extent to which intense low-frequency sound exposure poses a risk to the human auditory system. If such exposures are found to be harmful, the use of the C-weighting curve alongside the A-weighting curve (or some other suitable replacement frequency weighting function), would be recommended to ensure that low-frequency energy is adequately captured in sound-level measurements in entertainment venues.
Design goals for sound distribution in a “safe-listening venue”

McCarthy (2016) concisely summarises the overarching goal of modern sound-system design: “Same everywhere”. That is, every audience member should, within reason, experience sound of the same level and quality. The term “democracy of sound” has been used to capture the same principle (Hill et al., 2020).

Achieving this goal of uniformity of sound throughout the audience area would appear to be beneficial from a safe-listening perspective also. Measuring and controlling the sound level at any location within (or representative of) the audience area would in that case ensure that the exposure of all audience members would simultaneously be brought under control. In other words, no subset of the audience (those closest to the loudspeakers for example) would be at risk of experiencing damaging sound levels, while safe conditions were achieved elsewhere in the venue. All else being equal, “democracy of sound” leads to democracy of protection from hazardous sound levels.

This is promising, as it implies an alignment between the ambitions of the sound engineer and those of the individual or organisation promoting safe-listening practices. Sound quality need not be compromised to achieve safe-listening conditions: the two can go hand-in-hand. The challenge lies in achieving such uniformity of sound, as a range of acoustic and electro-acoustic factors conspire to make this difficult. Several of these factors are covered in greater detail in PART III of this report. Here, it is sufficient to note that the ideal of perfectly uniform coverage of the audience area is rarely achievable in practice.

While uniformity across the audience area is generally desirable, this does not mean that the sound level should necessarily be the same throughout an entire venue. It is common for bars (and sometimes other vendor stands) to be located within the performance space. These are areas where effective verbal communication is required, which will be facilitated by reduced sound levels. Some audience members may at times also wish to move to a slightly quieter location for respite from high sound levels, while not wishing to leave the performance altogether. This speaks to the need for careful consideration of the intended purpose(s) of all areas within a venue and the implementation of a sympathetic acoustic and sound-system design.

Indoor versus outdoor venues

The general goal of spatial uniformity of sound across the audience area applies equally to both indoor and outdoor venues. However, there are certain considerations specific to each type of venue which may influence how that goal is best achieved, and, indeed, the extent to which it is achievable.

Indoor venues

The primary acoustic difference between indoor and outdoor venues is the presence of room reverberation indoors. Reverberation is the name given to the multitude of reflections that occur as sound repeatedly bounces off a room’s surfaces. These reflections cause sounds to persist for up to a few seconds after they have been produced, with the sound level in the room gradually decaying until it fades into the ambient noise. The length of time that it takes for the sound to decay by a set amount is called the reverberation time (RT). The RT is principally determined by the volume of a room and the total amount of sound absorbing materials it contains.

One effect of reverberation is to “spread” sound energy, making for a more even sound level throughout a room. However, this reverberant sound energy generally will not be what the sound
engineer wishes for the audience to hear: the sound engineer would rather the audience hears primarily the sound coming directly from the loudspeakers, over which he or she has greater control (McCarthy, 2016). Reverberation has the effect of “flattening” modulations within a sound signal, which can impair the clarity of music or the intelligibility of speech (Kuttruff, 2009). Turning up the volume in an attempt to drown out or overpower unwanted reverberation is doomed to fail, although some (untrained) sound engineers may still attempt this. The only effective way to deal with excessive reverberation is by minimising its excitation in the first place (Mapp, 2003).

A further effect of reverberation is to increase the sound level within a room, due to the summation of the very large number of reflections that keep sound energy “trapped” within the room (Kuttruff, 2009). In indoor venues especially, one of the primary reasons why the PA system gets turned up loud is to overcome the sound coming directly from the band, backline, and stage monitors (Mulder, 2016). Unless the sound from the PA system is at the very least comparable in level to these other sources, the mix engineer will not have adequate control over the sound delivered to the audience. Acoustic drum kits and overdriven guitar amplifiers can be extremely loud to begin with, and their level will be further exaggerated by an overly reverberant room.

As an example, consider the scenario depicted in Figure 3a. A live music performance takes place in a small indoor venue (10 m x 7 m x 4 m) that features almost exclusively hard surfaces (wooden floor, exposed brick walls, plaster ceiling). The only significant sound absorption comes from the audience itself, which will absorb sound at mid-to-high frequencies (Adelman-Larsen et al., 2010). This room has a mid-frequency RT of around 1.2 s when occupied. The SPL that would be generated throughout the room (i.e. well away from the stage) by an enthusiastic drummer can be calculated and is estimated to be 102 dB $L_{Aeq}$ (see Appendix I). The commonly recommended limit of 100 dB $L_{Aeq}$ (Berglund et al., 2000) is therefore exceeded before the PA system has even been turned on. The sound engineer will need to turn the PA system up to a level that allows vocals and other instruments to be heard over the sound of the drums, raising the total SPL even further.

Figure 3b depicts the same room, but with some simple acoustic treatment installed. This takes the form of a heavy drape on the wall behind the drum kit, and an array of porous absorbers suspended 30 cm below the ceiling. These basic measures reduce the occupied RT of the room to around 0.6 s, and the predicted SPL from the acoustic drum kit is reduced to 99 dB $L_{Aeq}$. The sound engineer now has a chance of complying with a 100 dB $L_{Aeq}$ limit (or at least not exceeding it by as large a margin). As a further benefit of introducing the acoustic treatment, the sound quality within the room will be improved, on account of greater clarity and ease of mixing.
Figure 3  Example of the predicted sound pressure level generated throughout a small indoor venue by an acoustic drum kit before (a) and after (b) basic acoustic treatment. Note that these are the predicted levels from the drum kit alone, before the PA system has been turned on.

It is not just stage noise that must be overcome: the sound engineer will also wish to ensure that the sound from the PA system is loud enough to overcome sound generated by the audience (Mulder, 2016). At pop music events, crowd noise alone can easily exceed 100 dBA (Butterfield, 2006). The introduction of sound absorbing materials will help to reduce the SPL due to crowd noise too, meaning that the PA system may not need to be turned up quite so loud. The reduction in sound level is likely to be moderate, however, and so high levels of crowd noise will remain an issue at some concerts.

These examples make clear that to achieve high-quality amplified sound in indoor venues, the room acoustics must be conducive to allowing the sound engineer good control over the mix without needing to resort to excess sound level. Unfortunately, this is not the case in many venues, and sub-optimal room acoustics have been cited as one of the primary factors affecting sound engineers’ ability to comply with existing regulations designed to protect the audience’s hearing (Luypaert, 2016; Vereecke, 2016).

It is not just for the sound engineer’s sake that the acoustics of a live-music venue must be fit for purpose. In a subjective survey conducted by Adelman-Larsen and Thompson (2008), musicians, as well as sound engineers, reported that the acoustics of a venue were “very important” for their performance, and more than one in three musicians said they had chosen not to play in a hall on account of bad acoustics. More detailed advice concerning room-acoustic design for entertainment venues is provided in PART III.

Outdoor venues
At outdoor events, reverberation is rarely an issue, since most of the sound energy is free to disperse into the atmosphere. Isolated reflections (e.g. from site hoarding or hospitality trucks) are commonly encountered, but such late-arriving reflections generally impact on sound quality more so than overall sound level (McCarthy, 2016). In the absence of the dense reflections that occur in an indoor venue, uniformity of sound level across an outdoor audience must be achieved solely through...
direct sound from the PA system. This places significant demands on the design and output capability of the PA system, given the large audience areas needing to be covered at many outdoor events.

Outdoors, sound propagation is subject to varying meteorological conditions, including wind, temperature, and humidity (Davis and Jones, 1988). Wind and temperature gradients (variation in wind speed/temperature with height above ground) can cause large variations in sound level at locations far away from the source. This occurs when sound gets refracted due to changes in the effective speed of sound at different heights above ground level. Depending on the prevailing atmospheric conditions, sound energy can get bent upwards (away from the ground) or downwards (towards the ground). These effects are generally only significant over large distances, although at shorter distances (less than a mile), gustiness in the wind can still give rise to local gradient effects that influence sound propagation (Ingård, 1953).

As sound propagates through air, high-frequency energy is partially absorbed, resulting in an attenuation of the high frequencies which accumulates over distance. The strength of the attenuation is affected by relative humidity: dry air absorbs more sound than moist air (Davis and Jones, 1988). To the extent that atmospheric conditions are stable or predictable, these effects can be accounted for in system design. Indeed, some modern sound systems allow temperature and humidity data to be entered, which are then used to update the digital signal processing that is applied to the system. Through the use of different presets, the system’s characteristics can be updated throughout the day to compensate for changes in the weather. Even at the largest outdoor concerts, the audience will generally extend no more than a few hundred metres back from the stage, meaning that meteorological conditions will typically not have a pronounced effect on sound-level distribution across the audience area. Meteorological conditions can be expected to have a more significant impact on sound propagation to neighbouring properties, given the greater distances involved.

In practice, sound-system design at outdoor events will need to be conducted with the joint goals in mind of achieving even coverage across the audience whilst also meeting sound-level limits at noise-sensitive locations on and off site. Interested readers are referred to a report from the Audio Engineering Society (AES) Technical Committee on Acoustics and Sound Reinforcement for a detailed review of the management of sound exposure and noise pollution at large-scale outdoor entertainment events (Hill et al., 2020).

Venues that are hard to classify
Some live-music events take place in locations that exhibit characteristics of both indoor and outdoor venues, for example, events taking place in tents or marquees. Due to their lightweight construction, these structures may be relatively transparent to low-frequency sound3 (thus resembling the outdoor condition), but highly reflective at higher frequencies (resembling an indoor venue) (Gjestland and Tronstad, 2017). Very long RTs (up to 2.5 s) have been measured in unoccupied tent venues at mid frequencies (500–2000 Hz) in particular (DELTA SenseLab, 2013). It has been noted anecdotally that compliance with sound-level limits can be especially hard to achieve

3 Caution is needed in making generalisations about tents and marquees, since they pose complicated acoustical situations that are dependent on the size and shape of the structure and the tension on the faces; strong resonance effects can occur across the frequency range, including at low frequencies.
in these sorts of venues (Luypaert, 2016). This may be because the mid-frequency range in which these venues tend to be highly reverberant is also the range of greatest sensitivity for A-weighted measurements (the basis of most existing sound-level regulations). It is also a frequency range in which the vocal output from an enthusiastic audience can be expected to be particularly high, which may in some cases contribute to the exceedance of sound-level limits.
PART II: Review of the evidence-base on sound distribution in entertainment venues

Beach et al. (2019) comprehensively reviewed current policies and regulations in countries across the world designed to protect the hearing of patrons and audience members within entertainment venues. Most countries do not have such regulations, but a few, most notably in Europe, have developed detailed policies and regulations to address this issue. Here, we review the evidence-base on sound distribution in entertainment venues, anchoring the discussion around relevant requirements of current “safe-listening” policies and regulations.

Control of sound levels at most-exposed vs representative audience locations

Most current policies and regulations stipulate some form of sound-level limit that should not be exceeded, for example, $L_{Aeq,4hr} = 100$ dB. There is variation from country to country in the exact limit(s) imposed, as well as the required integration period and frequency weighting. Of direct relevance to the present report, there is also variation in where it is recommended (in some cases mandated) that the measurements should be made. For instance, Swiss regulations (Swiss Confederation, 2012), German industry standard DIN 15905-5 (Deutsches Institut für Normung, 2007), and guidelines from the UK Health and Safety Executive⁴ state that measurements should be made in the audience area at a position where the highest sound level is expected (i.e. at the most-exposed location). Where this is not possible, the measurement can be made at an alternative location (typically the FOH mixing position), with an appropriate correction made to account for the difference in sound level between the two locations. In other cases, for example under certain Belgian regulations (Government of the Brussels-Capital Region, 2017), Norwegian guidelines (Norwegian Directorate of Health, 2011), and a Dutch covenant (The Netherlands Ministry for Health Welfare and Sport, 2018), it is required that the sound level is measured at a “representative” location (often assumed to be at FOH).

This variability in approach raises several important questions related to sound distribution: (1) How much do sound levels vary across the audience area in different sorts of venue? (2) Can sound levels measured at FOH be considered representative? (3) If a correction is to be applied to account for a sound level difference between locations, how should this be implemented to ensure its validity? These questions are addressed in turn below.

How much do sounds levels vary across the audience area?

Measuring sound levels at multiple locations within a venue is challenging. Ideally such measurements would be made simultaneously, to ensure that all measurements are influenced by the same acoustic events (sound levels will vary somewhat from song to song and from set to set during a concert or festival); however, this requires as many sound level meters (SLMs) as there are measurement locations, which may be prohibitively expensive. Also, when measurements are made while an event is underway, access to the desired measurement locations is not always possible, and measurements may be subject to unquantified interference from crowd noise.

One approach to dealing with the problem of access is to fit volunteer audience members with wearable noise dosimeters, allowing their personal sound exposure to be logged. Interpretation of sound levels measured in this way can be challenging, however, as there may be relatively little

control over precisely when and where the volunteers do their listening. The reliability of dosimeter measurements can also be affected by differences in how the microphone is worn and the addition or removal of items of clothing (Butterfield, 2006; Tronstad and Gelderblom, 2016).

An alternative approach is to make measurements before an event begins, when the sound system can be excited by a reproducible test signal and controlled measurements can be made sequentially at different locations. However, it can be hard to find a suitable period during which the measurements can be made without interference from other noise-generating activities on site, especially at temporary events where setup time is usually limited (Brawley, 1991; Hill et al., 2019).

Also, the presence of an audience can change the acoustics of a venue, and so sound levels measured in an unoccupied venue may not be representative of those that will occur during the actual performance when the audience is present (Adelman-Larsen et al., 2010).

Despite these challenges, there are several studies in the literature that report the distribution of sound levels throughout one or more entertainment venues. In an early example, Brawley (1991) measured sound levels and spectra at ten different locations within each of three empty US sports arenas (capacity between 11,000 and 22,000) visited by a touring musical act. The same sound system was temporarily installed in each arena and excited by a pink-noise test signal. Taking the FOH mixing desk as a reference position, Brawley found that sound levels were within ±3 dBA of the reference across all tested audience locations (maximum range across audience locations within any one arena was between 2 and 6 dBA). Brawley concluded that the sound system could provide consistent coverage and SPL across the audience area in venues of varying size and capacity.

Other studies have reported a greater level of variability across the audience area at large-scale events. Mercier et al. (2003) used a combination of personal dosimeters and fixed SLMs to measure sound levels throughout the audience area at the Paleo Festival in Nyon, Switzerland, during July 2001. Based on measurements made during two sets performed on the largest of the festival’s four stages (capacity 25,000), Mercier et al. observed sound levels that varied by 8–12 dBA across the audience area (at distances between approximately 10 and 60 m from the stage). Interestingly, (A-weighted) sound levels were not always maximal for audience members standing closest to the stage, likely due to the use of flown loudspeaker arrays at either side of the stage that would have projected their maximum output towards a region further back into the audience area.

While flying the main loudspeakers above ground level is common practice at larger events, the subwoofers are still routinely placed at ground level in front of, on, or underneath the stage. This can result in pronounced front-to-back level differences across the audience area in the low-frequency range (30–100 Hz). For example, in a case study before the Pitchfork music festival in Chicago in July 2019, Hill et al. (2019) measured a low-frequency level difference of 17 dB over distances of around 2.5 to 30 m from the front of the stage (with audience absent). There is some evidence to suggest that, due to interference effects, the effective decay of the low-frequency sound pressure level with distance can actually be lessened when an audience is introduced (Shabalina and Vorländer, 2012). However, this is a complex effect, dependent on frequency, audience density, and precise measurement position, and substantial front-to-back low-frequency level differences are still to be expected when ground-stacked subwoofer arrays are used.

As explained in PART I, even dramatic variability across the audience area in the low-frequency range (30–100 Hz) will have negligible effect on A-weighted sound levels, since A-weighted measurements
are minimally sensitive to these low frequencies. Use of the C-weighting curve, instead of or in addition to A-weighting, would in principle capture this variation in the low-frequency range. While the risk of hearing injury associated with intense low-frequency exposure remains uncertain, it is noteworthy that individuals standing in the front row of the audience (as well as security and event personnel) at large-scale events may be consistently exposed to low-frequency levels in the range 120–130 dBC peak (Hill et al., 2019).

Turning from festival stages to smaller-scale, indoor venues, McGinnity et al. (2019) measured sound levels throughout six small- to medium-sized live music venues in Melbourne, Australia. As part of a longer-term study into the impact of a software-based sound-management system, McGinnity et al. used dosimeters mounted in fixed locations (in line with the main sound source on stage, at FOH, in the middle of the dance floor, at the bar, and at the ticket desk) to log sound levels during live performances. On average across venues, the stage was the loudest area, followed by the dance floor, FOH, and then the bar. If we assume that audience members standing directly in front of the stage would have been exposed to levels similar to those measured on stage, and that levels measured at FOH were representative of the rear of the audience area, then “Stage - FOH” should give a reasonable estimate of sound-level variability across the audience area. A secondary analysis of McGinnity et al.’s data reveals that levels on stage were on average 4.1 dBA higher than at FOH, although the range across venues was large (-2.9 to 8.7 dBA). The substantial variability across venues reflects the fact that the venues studied were highly heterogeneous in terms of size and layout, including in distance from stage to FOH.

A study by Griffiths (1991) is informative because identical methods were used in both indoor and outdoor venues of varying size. This study was commissioned by the UK Health and Safety Executive and aimed to quantify the difference in sound level between FOH and the “barrier location” (the nearest position to an operational loudspeaker that the audience were allowed to approach). As expected, sound levels at the barrier location were higher than levels observed anywhere else within the audience area in all but one venue (where the level at the barrier location was within 1 dBA of the maximum level). For outdoor concerts, the sound level at the barrier location was on average 8.1 dBA higher than at FOH (range 3.1 to 14.9 dBA). In indoor venues, the average difference was slightly smaller at 5.4 dBA (range -1 to 12 dBA). A smaller average level difference between FOH and the barrier location in indoor compared with outdoor venues is consistent with a typically smaller physical distance from front to back of the audience area combined with the partially “equalizing” effect of room reverberation. However, given the relatively small number of venues studied (four outdoor and seven indoor) and the wide variability even between venues of the same type, it is difficult to draw firm conclusions regarding any overall difference between indoor and outdoor venues.

A study conducted for the Danish Sound Technology Network (DELTA SenseLab, 2013) also measured sound levels across at least nine locations throughout the audience area at a range of venues (one large outdoor festival stage, two tented venues, and five indoor venues). The report states that sound levels at the individual measurement locations typically varied from the mean response by ±5 dB, although numerical data were not reported, preventing a detailed analysis.

Other studies have used personal dosimeters to log the sound exposure of workers performing different roles within venues, e.g. musician, sound engineer, bar staff, etc. (Butterfield, 2006; Gunderson et al., 1997). The results of these studies suggest that workers in different roles can have
very different sound exposures, though this is strongly influenced by differences in working patterns between roles, and few workers spend much of their time directly in the audience area. It is therefore not straightforward to interpret the results of these studies in terms of sound-level variability across the audience area.

To summarise, the extent to which sound levels vary across the audience area can be very different from one venue to another. Average values appear to be roughly 5 dBA for indoor venues and 8 dBA for outdoor venues. However, the range of variation even amongst venues of the same type is approximately 12 dBA, suggesting that such generalisations may not be particularly helpful. Even larger front-to-back level differences (up to 17 dBA and beyond) have been measured or predicted in the low-frequency range (30–100 Hz) in the case that ground-based subwoofers are used.

Can sound levels measured at FOH be considered representative?

In the face of such variability in sound levels throughout individual venues, it seems clear that sound levels measured at any one location are unlikely to be representative of the entire audience area. Typically, the FOH mixing position is located quite far back from the stage, and so levels measured at FOH will, in general, approximate levels experienced in the mid-to-rear part of the audience area.

A study by Tronstad and Gelderblom (2016) aimed to assess empirically whether levels measured at FOH are representative of those experienced by audience members. FOH measurements were compared with personal dosimeter measurements taken during outdoor concerts at the 2014 Øya festival in Norway. The dosimeters were worn by four student volunteers who were instructed to act as normal festival participants, moving around the site freely. The distributions of levels measured at FOH and by the personal dosimeters had similar central values. This suggests that levels measured at FOH can be used to assess audience exposure, however, some qualifying comments are in order.

Firstly, the number of volunteers used in this study was small. Secondly, Tronstad and Gelderblom noted that the distribution of sound levels measured with the dosimeters was broader than at FOH, suggesting that some participants will have experienced exposures lower than those at FOH, but others higher. Finally, participants in the study were forewarned about the risks of loud sound exposure at concerts, which may have influenced their behaviour (for example, by leading them to favour listening positions further away from the loudspeakers).

A similar, but larger-scale, study was reported by Borg (2015). Using modified hearing-aid technology to unobtrusively measure the SPL at the ears of audience members, the personal sound exposure of over 500 volunteer attendees at the Roskilde Festival in Denmark was logged between the years 2009 and 2014. Borg reported that sound levels measured at the ears of individual audience members showed a good correlation with measurements made simultaneously at FOH, suggesting that FOH measurements can serve as a useful guideline for audience exposure. However, example data plotted for one particular concert show a range of approximately 8 dBA in the levels experienced by nine different members of the same audience. Borg noted that such variability between individuals may have been due to many possible factors, including listening position relative to the stage, height of the audience member, whether there was an uninterrupted line-of-sight to the PA system, and meteorological effects.

In indoor venues, room reverberation will generally act to make sound levels more uniform throughout the audience area. In their study of long-term trends in sound levels at the UKA festival in Norway, Gjestland and Tronstad (2017) did not measure levels within the audience area (only at
FOH), but they did comment on the effect of reverberation on level variability. The UKA festival concerts were held in a large circus tent accommodating 4,000 people. This venue had significantly longer RT at high frequencies (where the tent fabric was reflective) than at low frequencies (which “leaked” through the tent fabric to a greater degree). Gjestland and Tronstad stated that attendees were located outside the critical distance (see PART III of the present report) from most of the loudspeakers in a more or less diffuse sound field; on this basis they assumed that A-weighted levels (more affected by mid-to-high frequencies) would be relatively stable across the audience area and that FOH levels could be considered representative for a major part of the audience. They noted, however, that attendees standing close to the subwoofers positioned at ground level along the front of the stage would have been exposed to higher levels of low-frequency sound. This raises an important point: it is possible for FOH sound levels to be representative of audience exposure at some frequencies, but not others. This will depend heavily on the acoustics and sound-system design of each individual venue.

The data from McGinnity et al. (2019)’s study of six small- to medium-sized live-music venues are also informative here. Sound levels measured in the “middle of the dance floor” during performances were on average 2.0 dBA higher than at FOH (range -2.2 to +4.4 dBA). This suggests that FOH measurements slightly underestimate levels in the middle of the audience area on average. However, the difference between FOH and the central audience area varies by more than 6 dBA across venues, suggesting that caution is required in assuming that a similar relationship holds for all venues.

To summarise, FOH measurements can generally be expected to correlate well with audience exposure, but the degree to which they are directly representative may vary substantially from one venue to another. On average, FOH measurements are likely to systematically underestimate audience exposure, at least compared to the most-exposed locations.

How should corrections for sound level differences between locations be implemented? If it is desired to ensure “safe-listening” conditions for all members of an audience, it will be necessary to apply a correction to FOH measurements to estimate exposure at the most-exposed audience location (FOH will often be the most practical location to measure sound levels during a live event, given typical access and security considerations). For such corrections to be valid, it is critical to take issues of sound distribution into account.

In their study of sound exposure at the Paleo festival in Nyon, Switzerland, Mercier et al. (2003) explicitly set out to establish whether it is possible to develop a general correction factor between the locations where the public is most heavily exposed and the FOH mixing desk. They found that the required correction factor depended on multiple factors, including meteorological conditions, local topography, audience density, and, especially, the spectral balance between low and high

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5 Note that the precise measurement position varied from venue to venue according to practical considerations, e.g. mounted to a pillar, suspended above the audience, etc. This is a source of between-venue variability in the measurements.

6 The development of a protocol for measuring sound levels in entertainment venues is the subject of a separate report commissioned by the WHO. Here, we comment only on the issue of correcting for a possible sound-level difference between measurement locations, in so far as this relates directly to the topic of sound distribution.
frequencies, which varies from one musical set to another. Across nine different concerts taking place on the same stage, the required correction factor varied across an 8-dBA range, from 5.3 to 13.3 dBA.

An effective way to account for the variation in spectral balance between sets could be to implement the correction on a frequency-dependent basis. In this approach, the level difference between FOH and the most-exposed location would be pre-measured on, say, a one-third-octave-band basis. Spectral levels measured at FOH during a performance would then be adjusted on a frequency-specific basis to estimate the spectrum at the most-exposed location. At this point, an appropriate frequency weighting can be applied (e.g. A-weighting), and an overall weighted level calculated for the most-exposed location. Such frequency-dependent correction is included as an option in some existing sound-management systems, for example, the system deployed across Norway under the Musikkutstyrordningen scheme (Støfringsdal, 2018). Despite this technological advancement, Støfringsdal notes that it is not trivial to obtain a robust measure of overall level differences between FOH and audience areas close to the stage. This is because audience members in these areas are exposed not just to sound from the main PA system, but also to sound coming directly from the stage, which is variable in nature and difficult to quantify.

A further potential complication arises from the use of correction factors measured in unoccupied venues to predict worst-case exposures in occupied venues. If the introduction of an audience changes the way in which sound propagates throughout the venue, the correction may no longer be valid. As noted previously, the introduction of an audience can have a complex effect on low-frequency sound propagation from ground-based subwoofers due to interference effects (Shabalina and Vorländer, 2012). Propagation of mid-to-high-frequency sound can also be affected by the introduction of an audience, since an audience forms an effective absorber of sound at these frequencies (Adelman-Larsen et al., 2010). If line-of-sight between a loudspeaker and a listening/measurement position is blocked by the audience, the level of high-frequency sound reaching that position is likely to be heavily attenuated. Through providing additional sound absorption, the introduction of an audience can also significantly reduce the RT of indoor venues in the mid-to-high-frequency range. The effect on RT can be expected to be most pronounced in venues that have a large audience area relative to their overall size (Hammond et al., 2018). To the best of the authors’ knowledge, the impact of these factors on the validity of correction factors between FOH and the most-exposed audience location has not been empirically assessed to date.

Requirements for an exclusion zone around loudspeakers

Some current policies and regulations include requirements restricting audience access to the area around loudspeakers, where sound levels are generally at their highest. For instance, guidelines from the UK Health and Safety Executive states that, wherever possible, patrons should not be allowed within three metres of any loudspeaker, and that under no circumstances should the separation be less than one metre. Similarly, a local restriction imposed by the City of Ghent in the Flanders region of Belgium requires that audience members should be kept at least one metre away from any loudspeaker (Beach et al., 2019). Austrian regulations (Republic of Austria, 2011) require patron access to the area around loudspeakers to be restricted if the sound level exceeds 100 dB L_{Aeq} in that area.

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How much do sound levels increase close to loudspeakers?

Sound levels can be expected to rise rapidly as one approaches a loudspeaker. Insight into the magnitude of this increase can be obtained by considering the hypothetical case of a point source in the free field; that is, an infinitely small sound source located well away from any boundaries or surfaces (Figure 4). In this scenario, moving from 3 m away from the source to 1 m away would see an increase in sound level of 9.5 dB. Continuing to approach to within 30 cm of the source would see a further increase in level of 10.5 dB. In combination, the level 30 cm from the source would be 20 dB higher than the level at 3 m.

![Illustration of rapidly increasing sound level as one approaches a sound source.](image)

These values are for the hypothetical case of a point source in the free field; the change in sound level as one approaches a real loudspeaker in a given environment may differ from the values shown here.

Put another way, if the maximum period for which it was considered safe to listen to this sound source from a distance of 3 m away was 4 hours, then at a distance of 30 cm it would be safe to listen for only 2 minutes. In reality, loudspeakers in entertainment venues are not point sources in a free field: they are physically large, contain multiple interacting drivers, and radiate into a complex acoustic environment. This means that the change in sound levels as one approaches a real loudspeaker may differ from the hypothetical case reported above. Nonetheless, this analysis makes clear that the increase in sound levels close to a loudspeaker could be very substantial indeed. Restricting access to the area immediately surrounding loudspeakers is therefore a sensible precaution, where this is practicable.

Should all loudspeakers be considered equal?

McCarthy (2016) details four different classes of loudspeaker as a guide to specifying the different components of a sound-reinforcement system. The maximum output capability, in terms of the peak SPL that these speakers can produce at a distance of 1 m, varies dramatically across the four classes. Specifically, McCarthy describes “Class 1” speakers as having a maximum output capability in the 110-119 dB range, while “Class 4” speakers, the most powerful models, have a maximum output capability of 140 dB and above. In light of this 30+ dB range, it clearly is inappropriate to consider all
loudspeakers as being equal. Thus, while restricting access to the area around loudspeakers based purely on a distance criterion (e.g. no access within one metre) may be a sensible precaution, it is important to keep in mind that this does not account for differences in output capability between loudspeakers.

It should be noted that the maximum output levels stated above are peak values, and long-term average sound levels from each class of loudspeaker can be expected to be significantly lower. Nonetheless, based on a 30 dB difference in relative output between a “Class 1” and a “Class 4” loudspeaker, if it was considered safe to listen to the Class 1 loudspeaker at a certain distance for 4 hours, it may be safe to listen to the Class 4 loudspeaker at the same distance for only 14 seconds.

**Requirements for a respite zone**

Current regulations in some countries, for example Switzerland (Swiss Confederation, 2012), France (République Française, 2017), and Belgium (Government of the Brussels-Capital Region, 2017), require venues to provide a quiet respite zone under certain conditions. This is to give patrons somewhere to go to rest their ears, away from high sound levels encountered elsewhere in the venue. Typically, the hourly sound level in the respite zone must be below a limit of around 80–85 dB $L_{Aeq}$.

There may exist cases where a venue wishes to provide a respite zone that is acoustically coupled to the main listening space, i.e. where airborne sound transmission is possible between the main listening space and the respite zone. Careful acoustic design would be essential in such cases, to achieve sufficient attenuation of sound from the main listening space. This would likely require a combination of extensive acoustic screening (i.e. acoustic barriers) and sound absorption to attenuate direct and reflected sound, respectively. Even with extensive treatment, such a solution is unlikely to be feasible in the majority of cases.

More commonly, venues will provide a respite zone in a different room from the main listening space. Adequate control of the sound level within the respite zone should in most such cases be achievable through standard architectural acoustic practices (e.g. specification of suitable wall and floor constructions capable of providing adequate sound insulation; provision of sound absorbing room-acoustic treatment within the respite room). If sound spillage from the main listening space into the respite zone through interconnecting doors is an issue, this may be solved by introducing a double-door arrangement, with the lobby area in between the two door sets treated with sound-absorbing materials.

**Requirements for optimized sound-system design**

Every venue and event is different, and the optimum means of delivering high-quality yet “safe” sound to the audience may differ accordingly. In some jurisdictions, this complexity is reflected in the regulations that have been introduced to protect patrons’ hearing. For instance, in the Flanders region of Belgium, event organizers are required to prepare a “noise plan” in the case of permanent sound installations that belong to the establishment (Departement Leefmilieu Natuur en Energie, 2016). The noise plan is to be prepared by a suitably qualified expert and must contain, amongst other information, evidence that the choice and arrangement of loudspeakers has been optimized to achieve the most efficient possible distribution of sound, as well as measurements of the sound level at a minimum of five locations throughout the venue (one of which is the main measurement location where sound levels are to be regulated). In the Brussels region, venues in which the highest
sound levels are expected must appoint a reference person who is responsible for ensuring not only the “best possible configuration” of the sound system, but also its appropriate operation so as to comply with the imposed sound-level limits (Government of the Brussels-Capital Region, 2017).

Requirements such as these, which necessitate professional input, will impose an additional financial burden on venue owners and event organizers, and may not be appropriate for all countries and contexts. Nevertheless, they highlight that successful compliance with recommended limits for sound exposure depends on appropriate sound-system (and acoustical) design, as well as competent operation of the system during ongoing use.

Summary

The primary requirement of most existing policies and regulations designed to protect the hearing of patrons in entertainment venues is some form of sound level limit(s) that should not be exceeded. There is variability in where it is required that measurements should be made.

Due to typical access restrictions and security considerations, it is common practice to make these measurements at the FOH mixing desk. Prior studies suggest that sound levels measured at FOH are likely to underestimate exposure across much of the audience area, significantly so for the most-exposed locations. The difference in sound level between FOH and the most-exposed audience location is, on average, around 5 dBA in indoor venues and around 8 dBA at outdoor events. However, this varies significantly between venues, even amongst those of the same type, and level differences in excess of 12 dBA have been observed. Even larger front-to-back level differences may occur in the low-frequency range (30–100 Hz) at large-scale events employing ground-based subwoofers.

Where regulations require sound levels to be controlled at the most-exposed audience location, a practical solution may be to measure levels at FOH, but to make an appropriate correction to account for the difference in level between FOH and the most-exposed location. The required correction would typically be pre-determined based on measurements made when the venue is unoccupied. Several factors may impact on the validity of this approach: 1) the overall (e.g. A-weighted) level difference between FOH and the most-exposed audience location will vary with the spectral balance of the music; 2) the presence of an audience can alter both direct-sound propagation and room reverberation, meaning that measurements made in an unoccupied venue may not be representative of those that will occur during an actual event; and 3) the estimated level at the most-exposed location will account primarily for sound coming from the PA system, and not for a highly variable and potentially significant contribution due to sound spillage from the stage and/or audience noise. The first point can in principle be circumvented by implementing the correction on a frequency-specific basis. The impact of points 2 and 3 is harder to quantify and, to the best of the authors’ knowledge, has not been studied empirically to date.

These complications notwithstanding, there may be merit in measuring and controlling sound levels at FOH, in so far as this will draw the attention of sound engineers (and other stakeholders) towards the risk of excessive sound levels and, hopefully, reduce the occurrence of extreme excursions beyond recommended levels.

Some current policies and regulations also specify an exclusion zone around loudspeakers. Such restrictions are well motivated: sound levels rise rapidly as one approaches a loudspeaker, and there are few, if any, circumstances where it would be appropriate for audience members to sit or stand
immediately next to a sound-reinforcement loudspeaker. However, taken in isolation, distance-based restrictions are somewhat arbitrary: the peak output capability of different types of loudspeaker used in sound-reinforcement applications can vary by upwards of 30 dB, meaning that it may be safe to stand one metre away from a particular make and model of loudspeaker, but extremely hazardous to stand at the same distance from another. Restricting access to the area around loudspeakers is therefore perhaps best considered as a supplementary requirement designed to move the “most-exposed” audience location further away from the loudspeakers (and therefore buy headroom to increase the sound level without causing dangerous conditions at the most-exposed location). On a practical note, it is also worth considering the factors that might drive patrons to occupy high-risk locations (e.g. over-crowding, poor sight lines to the stage) and assess what might be done to mitigate these, since patrons may not be occupying these locations out of free choice.

Some current policies and regulations stipulate that a respite zone must be provided with quieter average sound levels. Sound distribution, in terms of both the sound-system design and the venue acoustics, must be conducive to achieving the required level of sound attenuation between the main listening space(s) and the respite zone.

Ultimately, all venues and sound systems are different, and even a well-designed sound system in a venue with favourable acoustics will only meet safe-listening requirements if maintained and operated appropriately. Accordingly, in at least one European country, current regulations require venues to engage a suitably qualified professional to advise on an optimal sound-system design and for there to be a nominated person who is responsible for the upkeep and safe operation of the sound system. It must be noted, though, that imposing these as formal requirements places a considerable burden on venues and event promoters. An alternative approach would be to disseminate guidance and education around these topics, to help empower venue owners, event promoters and sound engineers to achieve high-quality sound without undue risk to hearing.
PART III: Sound distribution issues and solutions for venues supporting safe-listening practices

As discussed in PART I, an appropriate design goal for a “safe-listening venue” would be to achieve, as far as is reasonably practicable, uniformity of coverage over the audience area (i.e. those areas of the venue that are intended for active appreciation of the amplified sound). In PART II, we saw that such uniformity of coverage is relatively well achieved in some existing venues, but in others sound levels vary widely across the audience area. Here, we look in greater depth at the principal room-acoustic and electroacoustic design issues that influence uniformity of sound coverage. The focus, wherever possible, is on identifying practical steps that can be taken to promote safer listening conditions for the entirety of the audience, while preserving sound quality.

Venues for amplified music are rarely purpose built, and so it is usual for a room to exist first, and for a sound-reinforcement system to be designed to suit the characteristics of that room. Accordingly, we will address issues of room acoustics first, followed by issues of sound-system design. It is important to keep in mind, however, that the best results may be obtained by considering the room acoustics and the sound system together, and jointly optimising them as a combined system.

Room acoustics for amplified music

A rich literature exists on the desirable room-acoustic properties for concert halls and auditoria designed to host classical music performances (e.g. Barron, 2010; Beranek, 2004). In contrast, surprisingly little work has been done looking at optimum room-acoustic conditions for venues hosting amplified music events like rock and pop concerts, though the work of Adelman-Larsen and colleagues is a notable exception (Adelman-Larsen, 2014).

In the case of classical music performances, the venue acoustics must be satisfactory for both the audience and the musicians. The same holds true in the case of amplified music, although now there is an additional stakeholder: the sound engineer. It is the sound engineer’s responsibility to ensure that the musicians’ performance is delivered to the ears of audience members with clarity, integrity and vitality. The venue acoustics should be conducive to helping the sound engineer achieve this, and this leads to very different acoustical requirements for rock and pop venues compared to classical music venues.

Direct versus reverberant sound

In an indoor venue, the sound reaching the audience will comprise a mixture of direct sound from the loudspeakers and reverberant sound that has been reflected off the room’s surfaces (ignoring for a moment any sound coming directly from the stage). It is the direct sound from the loudspeakers over which the sound engineer has most control, and which will principally be relied on to convey the musical performance to audience members’ ears with clarity. The addition of a moderate amount of room reverberation will not be harmful to this process, but, if there is too much reverberant sound, speech intelligibility and musical clarity will be compromised (Kuttruff, 2009).

The level of the direct sound from the loudspeakers will fall off with distance, typically reducing at a rate of between 3 and 6 dB per doubling of distance, depending on frequency and the type of loudspeaker configuration. In contrast, the level of the reverberant sound will be more or less uniform throughout the room (unless the venue has a particular geometry that leads to highly
focused reflections, such as a domed ceiling), since it results from a multitude of reflections off all of the room’s surfaces. Thus, as one moves away from the loudspeakers, the ratio of direct to reverberant sound falls. The point at which the level of the direct sound becomes equal to the level of the reverberant sound is known as the “critical distance” (Kuttruff, 2009). Beyond the critical distance, reverberant sound will dominate, and there will be little further fall-off in sound level with increasing distance.  

To achieve the goal of delivering clear sound to all audience members, the ratio of direct to reverberant sound must be kept sufficiently high (Adelman-Larsen, 2014). In practice, this can be achieved through controlling the amount of room reverberation along with careful design of the PA system to direct sound towards the audience and away from the walls and ceiling.

Reverberation-time targets for amplified-music venues

In concert halls and auditoria designed to host classical music performances, a certain amount of room reverberation is considered desirable in order to add strength and warmth to the sound of orchestral instruments (Barron, 2010). In contrast, in venues hosting rock and pop concerts, sound-system design and operation is generally made easier when the venue is acoustically well damped, i.e. has a short RT (McCarthy, 2016). However, if the RT is too short, leaving the venue sounding overly “dead”, this can result in unsatisfactory conditions for the musicians: specifically, greater difficulty playing together as an ensemble and a feeling of disconnectedness from the audience (Adelman-Larsen et al., 2010; Støfringsdal, 2013). A balance is therefore required.

Based on an extensive survey of existing venues and taking into account the preferences of both musicians and sound engineers, Adelman-Larsen recommended that small-to-medium-sized venues for rock and pop concerts should have a flat RT profile across frequency (when unoccupied), with RT rising from approximately 0.6 s for venues of capacity 1,000 m³ to 1.2 s for venues of capacity 7,000 m³ (Adelman-Larsen et al., 2010). Longer RT values, up to around 2.5 s, may be suitable in large arenas of up to 50,000 m³ used for rock and pop concerts, although the evidence-base for this recommendation is less well established (Adelman-Larsen, 2014).

There is clear evidence that adequate control of RT at low frequencies (in the 63 Hz octave band and, especially, the 125 Hz octave band) is important for good sound quality in rock and pop venues (Adelman-Larsen and Thompson, 2008; Adelman-Larsen et al., 2010; DELTA SenseLab, 2013; Fuchs and Steinke, 2015). This is not surprising, given the prominence of low-frequency energy in amplified live music (cf. PART I of this report). While control of low-frequency reverberation appears to be critical for sound quality, it should be noted that this will have little direct bearing on overall sound levels, unless the C-weighting, rather than the A-weighting curve, is used. However, even in the case of A-weighted measurements, it is possible that excessive low-frequency reverberation could indirectly lead to higher sound levels: the sound engineer may incrementally raise the level of certain instruments in an attempt to overcome low-frequency muddiness in the mix, resulting in a spiralling increase in sound levels over time.

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8 While the critical distance is a helpful concept, it is important to be aware that, since loudspeaker directivity and material sound-absorption characteristics vary with frequency, the critical distance is also frequency-dependent: it will therefore not be possible to identify a single physical location in a venue that represents the critical distance for sounds of all frequencies (McCarthy, 2016).
Room modes

Room modes are another room-acoustic phenomenon that can affect the uniformity of sound levels throughout a venue. Room modes occur at frequencies where the distance sound travels between opposing surfaces of the room is an exact multiple of half a wavelength (Everest and Pohlmann, 2015). At these frequencies, sound bouncing back and forth between the surfaces undergoes systematic constructive and destructive interference, setting up a “standing wave” pattern. The result is alternating regions of high and low sound pressure throughout the room (Figure 5). In the presence of strong room-mode effects, there will not be spatial uniformity throughout a venue: listeners will experience a different bass response depending on where they are located.

Figure 5  
**Representation of the sound pressure distribution corresponding to a 3rd axial mode.**  
The sound pressure varies periodically with position in the room.

Room modes are exclusively a low-frequency issue. Above a certain frequency, multiple room modes will overlap, causing the fluctuations to average out and resulting in a spatially uniform sound field. The limiting frequency is commonly referred to as the “Schröder frequency” and can be calculated as $f_s = 2000 \frac{\sqrt{RT}}{V}$, where RT is the reverberation time in seconds and V is the room volume in m$^3$ (Kuttruff, 2009).

The output of most PA systems rolls off rapidly below around 30 Hz, so if a venue has a Schröder frequency below 30 Hz, room modes will generally be of negligible impact. Based on an analysis of Adelman-Larsen’s published data for 55 European rock and pop music venues (Adelman-Larsen, 2014), 65% of those venues have a calculated Schröder frequency below 30 Hz. It is only the smaller venues, typically with a volume below 3,000 m$^3$, that have a Schröder frequency above 30 Hz. The venue with the highest Schröder frequency (83 Hz) was also the smallest (capacity 630 m$^3$). This suggests that it is only in the smallest venues (e.g. in small bars or cafes) that room modes may be of practical concern, a point also noted by Adelman-Larsen (Adelman-Larsen, 2014).

Since room modes are a low-frequency issue, they will have negligible direct effect on A-weighted sound levels. However, as in the case of excessive low-frequency reverberation, strong room-mode effects could potentially lead to an indirect increase in A-weighted levels, if the sound engineer raises
levels in an attempt to overcome muddiness (or boominess) in the mix that results from the modal resonances. Where C-weighted measurements are used, strong room-mode effects could make it difficult to obtain reproducible measurements: the measured sound level could vary substantially from one position in the room to another (irrespective of distance from the loudspeakers), and, if musical material is used as the source signal (rather than an artificial test signal), measurements would be sensitive to the particular bass frequencies excited by the music in question.

Low-frequency modes are unavoidable in small rooms. In the rare case of a purpose-built venue, the impact of room modes can be lessened through judicious choice of room dimensions to spread the distribution of modes evenly across frequency and avoid multiple modes coinciding in any narrow frequency band (Cox et al., 2004). In practice, there will be few occasions on which the dimensions of a venue can be freely altered; it is therefore more common to tame problematic room modes through the introduction of low-frequency absorption (Fuchs and Zha, 2015).

Sound-absorption treatment

Room-acoustic issues, including excessive reverberation and prominent modal resonances, can often be dealt with by introducing sound-absorbing treatments to target the problematic frequency range(s). Some of these treatments are simple, low-cost additions to a venue; others involve more fundamental modifications to the design of the venue and hence may be more expensive and complex to install.

Acousticians use the absorption coefficient ($\alpha$) to describe how much sound energy a material will absorb. The absorption coefficient takes values in the range 0–1 (occasionally >1), with 0 meaning no absorption and 1 meaning full absorption. Intermediate values approximate the proportion of incident sound absorbed, e.g., if $\alpha = 0.5$, 50% of the incident sound energy will be absorbed and 50% reflected from a surface. The absorption coefficient is nearly always frequency dependent, since most objects and materials absorb more sound energy at some frequencies than at others.

There are two main types of sound-absorbing treatment: porous absorbers and resonant absorbers (Cox and D’Antonio, 2004). Porous absorbers are generally only effective at mid-to-high frequencies, while resonant absorbers can be tuned to absorb lower frequencies.

Porous absorbers work by dissipating sound energy as heat as the sound waves pass through a labyrinth of tiny, interconnected pores within the material (Cao et al., 2018). All soft materials such as curtains, carpet, and upholstery will provide a degree of porous absorption, although more efficient absorption may be obtained from dedicated acoustic treatments, typically manufactured from open-cell foam or from a fibrous material such as mineral wool. The introduction of porous absorption is generally one of the cheapest and most straightforward solutions to help control a venue’s acoustics.

Porous materials typically have an absorption coefficient close to zero at low frequencies, rising to a value closer to one at mid-to-high frequencies (Figure 6). Thus, porous materials are effective absorbers of sound only at mid-to-high frequencies. The reason porous materials don’t absorb much sound at low frequencies is because there is too little movement of air through the pores at these frequencies (Everest and Pohlmann, 2015). When sound waves strike a wall, the sound pressure is at a maximum immediately next to the wall and the velocity (movement of air molecules) is at a minimum (the wall is not easily moved). A little further away from the wall, the reverse situation occurs: sound pressure is at a minimum while velocity of the air molecules is at a maximum. A porous material will absorb sound effectively if it is placed in a location where the velocity of the air molecules
is high. How far back from the wall the position of maximum velocity occurs depends on frequency. At 2,000 Hz, the velocity maximum occurs 4.3 cm from the wall; a 5-cm thick porous panel mounted directly on the wall would therefore cover the position of high velocity and would be an effective absorber of sound at 2,000 Hz. In contrast, at 100 Hz, the velocity maximum occurs 86 cm from the wall; a porous panel almost one-metre thick would be needed to absorb sound effectively at 100 Hz, which is unlikely to be practicable. The low-frequency performance of a porous absorber can be improved, without increasing the amount of material needed, by spacing it away from the wall or ceiling (see Figure 6 for an example), although there are practical limits to the benefit that can be obtained in this way.

An audience will itself provide a substantial amount of absorption at mid-to-high frequencies (Figure 6), attributable mainly to the porosity of people’s clothing (Kuttruff, 2009). While most published data is for seated audiences in concert halls, Adelman-Larsen et al. (2010) confirmed by measurement that a standing audience, as is common at rock and pop concerts, absorbs about five times more energy at mid-to-high frequencies than at low frequencies. Thus, in some venues (depending on size, capacity, construction and furnishings), the audience may be relied on to provide sufficient absorption at mid-to-high frequencies, without the need for dedicated acoustic treatment targeting this frequency range\(^9\).

![Absorption coefficients for some common materials as a function of frequency (data from Cox and D'Antonio (2004))](image)

Since porous absorbers (including the audience) provide limited absorption at low frequencies, and given the importance of controlling the low-frequency RT to achieve good sound quality in rock and pop venues (Adelman-Larsen and Thompson, 2008), there is often a need for acoustic treatments that absorb sound more effectively at low frequencies. Resonant absorbers can meet this requirement.

\(^9\) It should be noted that if the audience is relied on to provide the bulk of sound absorption in the mid-to-high-frequency range, the acoustics of the venue may be unfavourable on nights of lower occupancy and when performing sound-checks in the unoccupied venue. It is also noted that in many medium and large venues, dedicated acoustic treatment may in any case be needed to satisfy regulations relating to the intelligibility of emergency announcements.
Resonant absorbers rely on a mass/spring system, where the mass vibrates against the spring and a damping of the resonance leads to sound energy being absorbed (Cox and D’Antonio, 2004). In a “Helmholtz absorber”, the mass is a plug of air at the opening to a cavity and the spring is the air contained within that cavity. In a “membrane absorber” (or “panel absorber”), the mass is a sheet of material and the spring is the air contained in the cavity behind the sheet. In both cases, the pressure component of low-frequency sound waves is converted to a velocity component by the vibrating mass, allowing a porous absorber placed behind the mass, where the particle velocity is now high, to absorb sound effectively. Membrane absorbers tend to be used to control low-frequency modal issues in small rooms, whereas Helmholtz absorbers are commonly used in large rooms and auditoria to provide broadband absorption (e.g. in the Queen Elizabeth Hall in London, England, which features a total of 2,300 Helmholtz absorbers – Higgins et al. (2016)).

In practice, Helmholtz absorbers are often constructed from a perforated sheet of wood or gypsum board, backed by a layer of porous absorption and with an air gap to the venue’s main structure (Cox and D’Antonio, 2004). This type of construction can be used in front of the walls or in the form of a suspended ceiling. Ceiling absorption systems are a natural choice for smaller music venues (providing there is sufficient space above the audience to install such a system), because they can provide much-needed absorption without reducing the useable footprint of the venue. By restricting the hole size, and therefore the open area of the perforated sheet, this type of absorber can be made less absorbent (i.e. more reflective) of sound at mid-to-high frequencies (as for the micro-perforated resonant absorber in Figure 6). This can help to avoid the over-absorption of mid-to-high-frequency sound if the venue already contains enough porous absorption, including the contribution from the audience (Adelman-Larsen et al., 2010). A partially reflective ceiling can also improve the sense of connectedness between the musicians and the audience (Adelman-Larsen, 2014; Støfringsdal, 2013).

In addition to the traditional approaches to sound absorption, innovative solutions have been brought to market to tackle specific problems. For example, Adelman-Larsen (2007) proposed an inflatable, thin and lightweight low-frequency membrane absorber, which can either be permanently installed within a venue, or, due to its light weight, taken from venue to venue and installed on a temporary basis. By inflating or deflating the absorber, it can be turned “on” or “off”, useful for multipurpose venues that may want variable acoustics depending on the type of performance, e.g. rock band vs. symphony orchestra. This inflatable system has been shown to be capable of selectively reducing a venue’s low-frequency RT, helping to achieve the flat RT profile across frequency that is characteristic of the most highly regarded venues for amplified music (Adelman-Larsen, 2015).

To summarise, the installation of porous absorption is a simple and relatively low-cost addition to a venue that will reduce the RT at mid-to-high frequencies and help keep A-weighted sound levels under control, especially if the venue was highly reverberant to begin with (cf. PART I of this report). This is consistent with advice from the UK Health and Safety Executive to protect the hearing of musicians and other employees, which recommends the use of carpet, drapes and ceiling tiles in venues (UK Health and Safety Executive, 2008). However, for the best sound quality in amplified music venues, it may be of prime importance to focus on controlling the RT at low frequencies (63 and 125 Hz octave bands), necessitating the use of resonant absorbers. Such measures may also help to keep C-weighted sound levels under control, although there will be minimal direct impact on A-weighted measurements. Indirect benefits are possible if the improved low-frequency clarity avoids the risk of spiralling level increases in the sound engineer’s pursuit of a clear mix.
Where it is within a venue’s (oftentimes limited) means, it is recommended that a competent acoustician is consulted to advise on the appropriate acoustic treatment for a venue. The acoustician will be able to make recommendations that take into account the current acoustics of the venue, the existing materials and construction, the most appropriate acoustic design targets (including, but not limited to, RT), and any budgetary or aesthetic constraints on the types of treatment that can be installed. The acoustician will also be able to advise on the most appropriate placement for any acoustic treatment, according to its intended use: reduction of RT, attenuation of high-intensity reflections that could otherwise compromise sound quality, or some other purpose (Adelman-Larsen, 2014; Støfringsdal, 2013). Finally, it is crucial that any acoustic treatment introduced into a venue is safe, meaning that it is non-carcinogenic and meets all relevant requirements for fire resistance, etc.

**Sound diffusion**

Another form of room-acoustic treatment, besides sound absorption, is sound diffusion. Rather than absorbing sound energy, a diffuser is designed to reflect sound in a way that spreads the energy as evenly as possible (Cox and D’Antonio, 2004). Dedicated diffusers are typically constructed either from curved (convex) surfaces or from surfaces that have a varying depth profile, e.g. a series of wells of different depths. A surface that comprises a patchwork arrangement of absorbing and reflecting areas will also provide a degree of sound diffusion.

Sound diffusion can be used as an alternative to sound absorption to treat many acoustical problems, for example, a late-arriving reflection off the rear wall of a venue that can be heard on stage as an echo, or uneven sound levels due to the focusing effect of a concave construction such as a dome or arch (Cox and D’Antonio, 2004). In classical concert halls, it is often preferable to treat acoustical issues using diffusion, rather than absorption, because of the need to preserve (and evenly distribute) as much of the sound energy produced by the orchestra as possible (Barron, 2010).

In venues designed for amplified music, the need to preserve acoustic energy will not be such a critical concern, since electrical power can readily compensate for any lack of acoustical gain (Adelman-Larsen, 2014). Nonetheless, the use of sound diffusion to solve acoustical problems may still be beneficial, especially if the use of sound absorption would result in over-absorption of sound at some frequencies, upsetting the flat RT profile across frequency that is desired for rock and pop venues (Adelman-Larsen et al., 2010). Particular areas of a venue that may benefit from diffusive treatment include the stage surroundings, to help distribute sound energy more evenly on stage (Adelman-Larsen, 2014), and areas of the upper side walls that receive intense direct sound from the loudspeakers, to distribute this energy more evenly across the audience area (Støfringsdal, 2013).

**Control of stage spill**

As noted in PART I, an issue in smaller indoor venues especially is the high sound levels that can occur on stage and the spillage of this energy into the audience area. Not only will this directly contribute to the overall exposure of those at the front of the audience, it may also lead to the sound engineer raising the output of the PA system to overcome the sound coming from the stage, increasing exposure for everyone in the venue (Mulder, 2016).

The most effective way to control stage spill is to reduce levels at source (e.g. by turning down guitar amplifiers, directing them away from the audience, moving them into an off-stage isolation booth, or replacing them altogether with a direct-injected signal and amplifier simulator). However, some instruments, such as acoustic drum kits, are inherently loud, and cannot easily be turned down. In
theory, it is possible to lessen the impact of such sources by absorbing as much of the sound energy as possible in the stage area, before it has chance to propagate towards the audience. Sandell et al. (2007) studied this empirically in an interventional case-study of a small live music venue in Sweden. As part of the intervention, the walls surrounding the stage were treated with sound absorbing panels of up to 100 mm thickness, the suspended ceiling was upgraded to a high-performance system capable of providing absorption down to 125 Hz, and a wool carpet was laid on the stage. Average sound levels across the audience area due to an acoustic drum kit played on stage before and after the intervention were 96.3 dBA and 92.6 dBA, respectively. Thus, the addition of the acoustic treatment reduced drum-kit spill to the audience area by almost 4 dBA. An even larger reduction of 7 dBA was measured in spill from the stage monitor loudspeakers to the audience area, although part of this reduction may have been due to a rearrangement that saw the monitors raised off the floor to bring them closer to the ears of a hypothetical musician (meaning that less output power would have been needed from the monitor to achieve a given SPL at the musician’s ears).

The results obtained by Sandell et al. (2007) demonstrate that making the area around the stage highly absorbing (alongside treatment elsewhere in the venue) can be effective in reducing stage spill to the audience. A further benefit of an acoustically well-controlled stage area is that it reduces the risk of “feedback” through the PA system, typically heard as a loud high-pitched screech (at potentially harmful SPLs). For these reasons, many sound engineers like the stage area to be acoustically dry, with a lot of absorption on the surrounding surfaces (Adelman-Larsen, 2014). It is common for this absorption to be provided through the extensive use of curtains, drapes, or other “stage textiles”. Støfringsdal (2013) recommends the use of dedicated low-frequency absorbers in the perimeter areas of the stage in such cases, to balance out the high-frequency absorption provided by the textiles. It must also be noted that very dry stage conditions may not accord with the wishes of the musicians, who generally prefer some (diffuse) early reflections from the surfaces around them to help them hear what they and their bandmates are playing and for a greater feeling of immersion (Adelman-Larsen, 2014). Adelman-Larsen (2014) recommends that, in general, the acoustics of the stage should be similar to those of the rest of the venue.

A complementary approach to reducing stage spill is to block the direct-sound path between an on-stage source and the audience, where this is practicable and acceptable to the performers. A typical application of this approach is the use of a clear screen, made of acrylic or poly-carbonate, placed in front of the drum kit, commonly known as a “drum shield”. In the case study by Sandell et al. (2007), the use of a partial-height (80 cm) drum shield was found to reduce drum-kit sound levels in the audience area by a further 4 dBA, without causing any noticeable change in the SPL experienced by the drummer (important for their own safety). It should be noted that, since the blocked sound is reflected back towards the drummer, a drum shield is likely to prove effective only if the surfaces at the rear of the stage area are made absorbing (as was the case in the study by Sandell et al.).

**Sound-system design**

**Designing for minimum spatial variance**

The consensus amongst the audio-engineering community is that an important goal of sound-system design, regardless of venue type, is to achieve uniformity of coverage across the audience area (Hill et al., 2020). That is, the aim should be to achieve minimum spatial variance in each of the following four categories (McCarthy, 2016):
- **Level**: differences in SPL across the audience area
- **Spectral**: differences in overall frequency response across the audience area (e.g. the balance between low and high frequencies)
- **Sonic image**: differences in perceived sound source location across the audience area (e.g. does the sound seem to come from the musicians on stage or from elsewhere?)
- **Ripple**: differences in fine-grained frequency response across the audience area due to interactions between multiple loudspeakers or between direct and reflected sound

From a safe-listening perspective, minimizing level and (to a lesser extent) spectral variance across the audience area is of primary concern. To preserve the highest possible sound quality, this should ideally be achieved without increasing variance in the other categories.

The design and optimization of modern sound systems can be complex, and the process is covered in detail by a number of textbooks (e.g. Davis et al., 2013; Davis and Jones, 1988; McCarthy, 2016). Here, we focus on identifying some basic principles that can help to achieve safer listening conditions for the entirety of the audience.

**Loudspeaker positioning**

A fundamental principle for achieving uniform sound levels across the audience area is to avoid a situation where some audience members are located much closer to the loudspeakers than others (McCarthy, 2016). This is because the level of the direct sound will decrease with distance from the loudspeakers, falling off at a rate of up to 6 dB for every doubling of distance.

Figure 7a depicts a worst-case scenario, yet one that is encountered in many small live-music venues around the world. The main loudspeakers are stacked at the front of the stage, close to audience head height, and there is no barrier to prevent audience members from approaching the loudspeakers. In this scenario, sound levels will be much higher at the front of the audience than at the rear. There are two reasons for this: 1) audience members at the front are many times closer to the loudspeakers than those at the rear; 2) the direct sound path from the loudspeakers towards the rear of the audience is blocked by the audience itself, which will cause significant additional attenuation at mid-to-high frequencies (Adelman-Larsen et al., 2010; McCarthy, 2016). A possible solution is shown in Figure 7b. By elevating the loudspeakers above head height, the “range ratio” between the nearest and furthest audience members is reduced, and a clear direct-sound path to the rear of the audience is established (McCarthy, 2016). Sound levels will be more even between the front and rear of the audience as a result.
Elevating, or “flying”, the loudspeakers in this way is in line with recommendations from the UK Health and Safety Executive (2008). But what if the venue has limited ceiling height and it is not possible to raise the loudspeakers far above the audience? Figure 7c shows a possible solution for such a scenario. The main loudspeakers are flown as high as the limited ceiling height will allow, and an additional set of ceiling-mounted “delay” loudspeakers are introduced part-way through the venue. These delay loudspeakers support the delivery of sound to the rear half of the audience, meaning that the main (front) loudspeakers need not be so loud.

The use of delay systems is commonplace at large outdoor events, but there is evidence that they can be helpful in achieving more uniform sound distribution in smaller indoor venues too (McCarthy, 2016; Ramakrishnan and Dumoulin, 2016; Sandell et al., 2007). For example, McCarthy (2016) describes a case-study on a challenging venue that was 14 m long, but that had a ceiling height of only 2.1 m. By introducing two rows of delay loudspeakers approximately 4 m and 8 m in front of the main loudspeakers, it was possible to almost completely eliminate a front-to-back level difference that had started out greater than 10 dB (and which was estimated to have been 20 dB or more when an audience was present).

A downside to elevating the loudspeakers is that it can potentially worsen sonic-image variance. For audience members at the front, it may seem that the sound is coming from overhead, rather than from the musicians on stage. At the cost of increased system complexity, the use of front-fill loudspeakers (smaller loudspeakers located at the lip of the stage that support sound delivery to just the first few rows of the audience) can help to address this problem (McCarthy, 2016). The use of delay loudspeakers can also introduce concerns related to sonic imaging. For instance, might audience members at the rear identify the delay loudspeakers as the source of the sound, rather than the musicians on stage? In practice, this can be mitigated through careful optimization of the system. Specifically, by setting the relative level and time delay between the main loudspeakers and the delay loudspeakers correctly, the impression can be given that all of the sound comes from the front of the venue, ensuring a sense of connectedness to the performance (McCarthy, 2016).

A natural extension to the idea of delay loudspeakers is to move to a situation where there are no longer any “main” loudspeakers at all, and all areas of the audience receive direct sound from their own nearby loudspeaker(s). Such “distributed systems” most commonly take the form of a regular pattern of overhead loudspeakers (Davis et al., 2013). This type of system is more often found in shops, restaurants, and meeting rooms than in music venues, although ceiling-mounted
Loudspeakers have been reported to help reduce sound exposure in a nightclub environment by keeping the music focused on the dance floor (UK Health and Safety Executive, 2008). An appropriately designed ceiling loudspeaker system may be an appropriate choice where the focus is on reproduction of pre-recorded music (e.g. gyms, some bars and clubs, etc.). If enough loudspeakers are used (and if the ceiling height is sufficient), these systems are capable of achieving excellent uniformity of coverage (Davis et al., 2013). However, due to poor sonic imaging, fully distributed systems are unlikely to be suitable for live-sound reinforcement, where it is important that the sound is perceived as originating from a common location corresponding to the position of the performers on stage (McCarthy, 2016).

A contemporary extension to the distributed-system concept comes in the form of so-called “source-oriented systems” (Hill et al., 2020), such as L-ISA™ from L-Acoustics and Soundscape™ from d&b audiotechnik. Taking advantage of rapid developments in computing power, these state-of-the-art systems aim to achieve a uniform, immersive listening experience for all members of an audience, in which individual instruments and sound sources can be virtually positioned in three-dimensional space. To achieve this requires that each audience member hears overlapping sound from multiple loudspeaker arrays, and thus the total number of loudspeakers deployed in such systems tends to be large. To the extent that these systems are successful in realizing their design goals, they may set a new gold standard for uniformity of coverage across the audience area. However, published data on these emerging technologies is limited. Given the expense and complexity involved, for the time-being at least, the use of source-oriented systems is likely to be reserved for high-end venues and productions.

A final point is worth noting in relation to the use of distributed loudspeaker systems, including delay loudspeakers: if these are not set up correctly (e.g. a delay loudspeaker is inadvertently turned up louder than it should be), then a situation could potentially arise in which the most-exposed location within a venue is not at the front of the audience, close to the main loudspeakers, but rather directly in front of the delay loudspeaker. Even loudspeakers which are relatively small in size can be capable of producing extremely high SPLs in the mid-to-high frequency range that is emphasized in A-weighted measurements. Care is therefore needed to assess possible sound-exposure risks from all loudspeakers in a venue.

**Loudspeaker directivity**

Loudspeakers do not emit sound equally in all directions, i.e. they exhibit directivity. This directivity is helpful, in that it can be exploited to: 1) focus sound where it is wanted (i.e. on the audience, not on the walls and ceiling), which helps to keep the ratio of direct to reverberant sound high; 2) minimize interference between loudspeakers, allowing multiple loudspeakers to be used where necessary, each targeting a different part of the audience; and 3) (partially) compensate for the natural attenuation of sound level with distance, allowing more similar sound levels to be achieved at near and far audience locations.

As noted in PART I, most loudspeakers are more or less omnidirectional (light a bare light bulb) at low frequencies, but they can be highly directional (like a torch beam) at high frequencies (Davis et al., 2013). Different designs of loudspeaker exhibit different directivity patterns as a function of frequency (McCarthy, 2016). Furthermore, when multiple loudspeakers are combined into a “cluster” or “array” (as is nearly always the case in modern sound-reinforcement systems), the combined directivity pattern can become either broader or narrower, depending on the directivity pattern of the individual loudspeakers.
loudspeakers and the way in which they are combined (McCarthy, 2016). With advances in digital signal processing (DSP), it is now common to apply individual level, delay and phase settings to each loudspeaker within a cluster or array, which can further modify the directivity pattern and even electronically steer the sound in a particular direction (Davis et al., 2013).

The task of the sound-system designer is to optimally match the coverage shape of the loudspeaker(s) to the shape of the audience area, with the end goal being minimum spatial variance across the audience (McCarthy, 2016). Given the level of complexity involved, this task is typically undertaken with the aid of dedicated software tools (see Figure 8 for an example).

Figure 8  Example of sound-system design for an indoor venue being conducted with the aid of a software tool capable of predicting SPL across the audience area for different loudspeaker configurations (Soundvision™ software from L-Acoustics)

Line arrays
The most commonly used loudspeaker configuration in modern-day large-scale sound reinforcement is the line array, a vertically stacked collection of identical loudspeaker units flown above ground level (Hill et al., 2020). The line array offers operational benefits, such as ease of rigging (Swallow, 2010), but also acoustical benefits. Specifically, line arrays have excellent ability to “throw” sound to the back of larger audiences, and they also have a narrow directivity pattern in the vertical plane, meaning that unwanted sound propagation towards the ceiling can be minimized in indoor venues (Adelman-Larsen, 2014).

The ability of a line array to provide effective directional control is limited to a certain frequency range. At the low-frequency end, the limitation is dictated by the length of the array: a longer array is required to achieve directional control down to lower frequencies (Davis et al., 2013). At the high-
frequency end, the limitation is dictated by the minimum spacing that can be achieved between the high-frequency elements of adjacent loudspeaker units: above a certain frequency, the vertical directivity pattern will start to break up and significant energy will be radiated in unwanted directions (Feng, 2014).

The reason line arrays are effective at covering larger source-to-receiver distances is because, at least for mid-to-high frequencies and for listening positions not too far away from the array, the fall-off in level is only 3 dB per doubling of distance, rather than the usual 6 dB (Adelman-Larsen, 2014). This helps to deliver direct sound to the rear of large audience areas (McCarthy, 2016). At lower frequencies and beyond a certain (frequency-dependent) distance from the array, the fall-off in level gradually reverts to the usual 6 dB per doubling of distance. To achieve uniform sound levels from front-to-back of the audience, “variable curvature” line arrays are almost always used in practice, in which the lower elements in the array are increasingly bent downwards (“J-shaped”) to point towards the front of the audience. By carefully optimising the angles of the downward facing loudspeakers (and sometimes also reducing their output level compared to the “long-throw” loudspeakers positioned at the top of the array), the fact that audience members at the front are much closer to the loudspeakers can be compensated for and an equal level distribution obtained (Adelman-Larsen, 2014).

Line arrays are undoubtedly a powerful solution to help achieve uniform audience coverage in many cases, although they are not always needed or, indeed, desirable. In some venues, the use of a more traditional “point-source” loudspeaker system may be more suitable (McCarthy, 2016). The most important consideration is to choose the appropriate system for the given space.

Subwoofers
Subwoofers, loudspeakers which are dedicated to reproducing low-frequency (30–100 Hz) sound, are well researched in terms of their design and optimization (e.g. Hill et al., 2010). By taking advantage of the long wavelengths (3–11 m) of sound at these frequencies, engineers can use predictable patterns of cancellation between clusters of subwoofers to direct the sound to where it is wanted (usually in a forward direction, towards the audience and away from the stage). As discussed in PART I, the subwoofers make a major contribution to the overall energy present in amplified live sound, although whether intense low-frequency sound poses a significant risk to the human auditory system remains poorly understood.

As discussed in PART II, even when the main loudspeakers are elevated above ground to help achieve uniform coverage across the audience area, it remains common practice to place the subwoofers at ground level, either on, under, or in front of the stage (Hill et al., 2010). In many cases, the front row of the audience may be only a couple of metres away from the subwoofers, resulting in exposure to extreme SPLs at low frequencies (Hill et al., 2019). Flying the subwoofers, as for the main loudspeakers, can help to achieve more uniform low-frequency SPL from front-to-back of the audience, and hence protect the front rows from excessive exposure (Corteel et al., 2018). Flown subwoofer systems face practical challenges, however, due to the large size and weight of the subwoofers and the need for additional rigging to support them. For these reasons, the use of flown subwoofer systems remains rare at present.
Low-frequency coherent interference between spaced loudspeaker arrays

The most common configuration for the main loudspeakers in live-sound reinforcement is a spaced left/right system, in which identical loudspeaker arrays are hung on each side of the stage (McCarthy, 2016). Sometimes, the subwoofers are similarly positioned on the left and right sides, either as ground-stacked clusters or vertical arrays flown alongside the main loudspeakers (Hill et al., 2010). To ensure that all listeners can hear all instruments, live sound is usually mixed in mono, with an identical signal being sent to the left and right loudspeaker systems (McCarthy, 2016). Unfortunately, this results in coherent interference, with sound from the left and right loudspeaker systems adding constructively or destructively depending on frequency and the relative distance to each loudspeaker system.

At high frequencies, coherent interference between the left and right loudspeaker systems may affect sound quality (ripple variance), but it is unlikely to have much effect on overall sound exposure. However, at lower frequencies, especially in the subwoofer range, coherent interference can cause large-scale SPL variation horizontally across the audience area. In particular, it is common for a narrow region running down the centre of the audience to experience considerably higher low-frequency SPL than areas to either side of the centre, the so-called “power alley” effect (Hill et al., 2010). Listeners located centrally may therefore be exposed to significantly more low-frequency energy than those located to one side. As this is a low-frequency effect, it will not be apparent in A-weighted sound-level measurements, though C-weighted measurements will be affected.

A physical solution to the problem of low-frequency coherent interference is to replace the spaced left/right systems with a single, centrally located array/cluster. Indeed, a flown central subwoofer configuration is thought to be optimal for achieving uniform low-frequency coverage across an audience, both from left-to-right and front-to-back (Corteel et al., 2018). However, flown central loudspeaker arrays are often ruled out due to visual production requirements, including the need to maintain unobstructed sight lines into the stage canopy (Hill et al., 2010). Where the traditional left/right arrangement is retained, an alternative approach is to decorrelate the electrical signals sent to the left and right loudspeaker systems (Hill, 2017). This can be achieved in a rudimentary manner by applying slightly different equalization settings to the left- and right-side signals. An emerging approach, which may be more effective, uses diffuse signal processing to decorrelate the left- and right-side signals in a perceptually transparent manner (Moore and Hill, 2018).

While removing the “power alley” effect can be seen as desirable, it is important to note that many sound engineers may have become so accustomed to mixing shows from within the power alley that when the effect is removed they feel the sound to be bass-light and therefore increase the overall subwoofer system level to compensate. This speaks to the importance of ensuring that the sound engineer is made aware that the system has been calibrated for even audience coverage.

In-ear monitoring for performers

As discussed previously under venue acoustics, spillage of high sound levels from the stage into the audience area can be particularly problematic, especially in smaller indoor venues (Mulder, 2016). In some cases, stage spill could be so high as to exceed recommended limits before the main PA system has even been turned on. Alongside loud acoustic instruments (e.g. drums) and backline amplifiers, sound from on-stage monitor loudspeakers can be a major contributor to stage spill. After all, to allow the musicians to hear themselves, the level from the monitors must be loud enough to overcome what are often already very high sound levels on stage.
While the application of sound absorbing treatment to the stage surroundings can help to reduce monitor spill to the audience area (Sandell et al., 2007), a more effective solution is to remove (or at least minimize) the use of stage monitors altogether. This can be achieved through the use of in-ear monitoring (IEM), where the musicians wear individual earphones that provide them with their own personal mix of the performance. McGinnity et al. (2019) found that, in venues where IEM was used, the sound level on stage was below that measured in the audience area or at FOH. This contrasts with venues in which traditional on-stage monitor loudspeakers were used, in which the sound level on stage was higher than anywhere else in the venue. As noted by McGinnity et al., the increasing use of IEM could help to reduce audience exposure, because the sound engineer no longer has to compete with sound from on-stage monitor loudspeakers. However, IEM does impose more complex equipment requirements, and some musicians may prefer not to use IEM either because they feel it creates a sense of detachment from the environment (Berg, 2017) or because of concerns about the risk of damaging their own hearing through IEM use.

A case study from Sweden

The room-acoustic and electroacoustic issues and suggested solutions relating to sound distribution in “safe-listening” venues discussed in the preceding sections are evidence-based and well known to practicing acousticians and live-sound engineers. However, at present, there is little published literature addressing whether the application of these principles is effective at reducing audience sound exposure in entertainment venues. One notable exception is the interventional study of a small (capacity <300) live-music venue in Sweden by Sandell et al. (2007).

Prior to the intervention, the acoustics of the venue were judged to be poor, with acoustically reflective materials on the walls, ceiling and floor. The configuration of the PA system resembled the “worst-case” scenario depicted in Figure 7a, with the loudspeakers stacked at ear height and firing straight into the audience. The mean SPL at the “most-exposed” location (in front of the loudspeakers) measured across two concerts was 108 dB L_{Aeq}, exceeding all current regulations in place around the world (Beach et al., 2019). Furthermore, a large difference (16 dBA) was measured between the most- and least-exposed audience locations during a concert.

A multi-stakeholder group was formed to make democratic decisions regarding the acoustic renovation of the venue. Members of the group represented diverse viewpoints, from those interested in upholding the artistic freedom to play loud music at any level, regardless of the risk of hearing damage, to those interested in upholding governmental regulations. The renovation was informed by the use of room-acoustic prediction software, which could model the effect of changing the surface materials on the venue’s acoustics and also optimize loudspeaker positioning to achieve uniform coverage across the audience area.

The renovation involved changes to both the venue acoustics and the sound-system design. Regarding the acoustics, the major change was the introduction of significant amounts of sound-absorbing treatment in the form of wall panels (around the stage), ceiling panels (throughout), and a wool carpet on stage. Importantly, the ceiling absorption (100-mm thick glass-wool panels wrapped in a micro-perforated plastic film and mounted with an air gap to the structural ceiling) would have been capable of providing significant absorption in the low-frequency range (125 Hz octave band) crucial for sound quality in amplified music venues (Adelman-Larsen, 2014). A complete redesign of the sound system resembled the solution depicted in Figure 7c, with the main loudspeakers elevated to ceiling level and two additional delay loudspeakers introduced midway through the venue (also
ceiling mounted). Four subwoofers were also introduced, incorporated into a new stage construction. A further minor electroacoustic change was the elevation of the stage monitors off the floor to bring them closer to the musicians’ ear height (meaning that the same SPL could be achieved at the musicians’ ears with less output from the monitors).

The acoustic renovation of the venue proved successful. Stage spill to the audience area from an acoustic drum-kit was reduced by 4 dBA, and stage spill from the monitor loudspeakers was reduced by 7 dBA. The redesigned sound system was able to achieve uniform coverage (within 3 dBA) across the core audience area. Most importantly of all, audience sound exposure during real concerts seems to have been reduced. While Sandell et al.’s data do not lend themselves to a robust statistical analysis, the mean SPL of 108 dB $L_{Aeq}$ that was measured at the most-exposed location across two concerts prior to the intervention was reduced to 99 dB $L_{Aeq}$ when measured across six concerts post-intervention. This reduction of 9 dBA brought levels into compliance with a 100 dBA limit recommended by the Swedish government at the time.

Overall, Sandell et al.’s findings offer promise that by improving a venue’s acoustics and upgrading the PA system to achieve more uniform sound distribution, audience sound exposure can be brought within recommended limits, even in the challenging case of a small, indoor rock venue. In most cases, such a reduction in exposure will be accompanied by an enhancement of, not a compromise to, the sound quality enjoyed by audience members. However, it is important to keep in mind that, in the United Kingdom at least, but probably elsewhere too, most small live-music venues operate under significant financial pressure (Music Venue Trust, 2015). The sort of full-scale acoustic renovation described by Sandell et al. may be out of reach for some venues.
Conclusions

Design goals for safe-listening venues
Designing for safe listening does not mean compromising on sound quality. The best sound systems are designed for spatial uniformity, i.e. all audience members should ideally hear sound at the same level and the same quality. If this goal is met, monitoring and regulating audience sound exposure becomes easier: sound levels measured anywhere in the audience area can be assumed to be representative of those that all audience members are experiencing. Where this goal is not met, there is a risk that some audience members may be exposed to hazardous sound levels, whilst for others the sound level is too low for the listening experience to be satisfactory.

Some venues may, however, deliberately choose to target lower sound levels in certain areas, for example, in bar or lounge areas, or towards the rear of a performance space. This can improve patron choice and comfort. As such, it is unlikely to be desirable to mandate a specific limit for the maximum allowable variation in sound levels throughout a venue. What matters from a health perspective is the sound levels that audience members experience in the most-exposed location(s). Achieving uniform sound distribution is the way in which sound levels can be brought under control at the most-exposed location(s), while ensuring that the sound level remains adequate for the rest of the audience.

Consequences of sub-optimal venue acoustics
Sub-optimal venue acoustics may lead to difficulty complying with sound-level limits. In smaller indoor venues, recommended limits may be exceeded purely by sound from on-stage sources, including drum kits, backline amplifiers, and monitor loudspeakers, before the main PA system has even been turned on. This is likely to be a problem especially in venues that feature predominantly hard surfaces, and which are therefore highly reverberant. For similar reasons, adhering to sound-level limits in tented venues may be particularly challenging because of the long mid-frequency reverberation times that sometimes occur in these enclosures.

A secondary, indirect way in which poor venue acoustics (and/or poor sound-system design) may lead to higher audience sound exposure is if the sound engineer pushes up levels in pursuit of a clearer mix. Over time, it is possible for sound levels to spiral upwards, all the while not fixing the underlying lack of clarity which stems from poor acoustics. It is possible that the acoustical problems giving rise to the lack of clarity may originate in the low-frequency range. While A-weighted sound-level measurements are insensitive to low frequencies directly, if the levels of instruments such as vocals, guitars or keyboards are increased in an attempt to achieve greater clarity, this is likely to increase A-weighted sound levels.

Spatial variability in sound levels throughout existing venues
The amount of spatial variability in sound levels that is observed in existing venues varies widely. The difference in sound level between the FOH mixing desk and the most-exposed audience location is, on average, around 5 dBA in indoor venues and 8 dBA at outdoor events. However, this varies significantly between venues, even amongst those of the same type, and level differences in excess of 12 dBA have been observed. In the worst cases (e.g. where the main loudspeakers are at audience head height and fire straight into the front rows of the audience), the difference in sound level between the front and rear of the audience could exceed 20 dBA.
It is common for the spatial uniformity of sound levels to differ markedly at low frequencies compared to mid-to-high frequencies. In part, this reflects inherent differences in the way that sound propagates at low versus high frequencies. However, another major factor is that the lowest frequencies (30–100 Hz) are often reproduced by dedicated subwoofers, which may be placed in a different physical location from the main loudspeakers (often at ground level along the front of the stage). The subwoofers make a major contribution to the overall energy present in amplified live sound (though this is not captured by A-weighted measurements, which are largely insensitive to such low frequencies). It is possible, and indeed common at large-scale events, for some audience members to be exposed to extreme levels of low-frequency sound, even when A-weighted sound levels have been brought under control. Further research is needed to understand the extent to which exposure to intense low-frequency sound poses a risk to human hearing.

Implications for sound-level monitoring
In practice, it is usually most convenient to monitor sound levels at the FOH mixing desk. Given the variability in sound levels that is observed in many venues, it is sometimes required that such measurements are corrected so as to estimate levels at the most-exposed audience location. There is little empirical research looking into the validity of these corrections. Challenges remain in accounting for the variable effect of loud on-stage sound spilling into the audience area, differences in spectral content across bands and genres, and the differences in venue acoustics that can occur between the unoccupied (in which the required correction factors are usually measured) and occupied states.

Sound levels close to loudspeakers
Sound levels can be expected to increase rapidly as one approaches a loudspeaker. The increase when approaching from a distance of 3 m to a distance of 30 cm could be as much as 20 dB. Restrictions on how close audience members are allowed to get to the loudspeakers are therefore well motivated, if hard to implement in some venues. Distance-based restrictions are also somewhat arbitrary, since the peak output capability of different types of loudspeaker used in sound-reinforcement applications can vary by 30 dB or more. In other words, it may be much more hazardous to stand a certain distance away from some models of loudspeaker than others, this of course also depending on how hard the loudspeakers are being driven at the time.

Safe-listening regulations requiring professional input
In at least one European country, current regulations require venues to engage a suitably qualified professional to advise on an optimal sound-system design and for there to be a nominated person who is responsible for the upkeep and safe operation of the sound system. Such requirements impose an additional financial burden on venue owners and event organizers, and may not be appropriate for all countries and contexts. Nevertheless, they highlight that successful compliance with recommended limits for sound exposure depends on both appropriate sound-system design and competent operation of the system during ongoing use.

Venue acoustics for amplified music
For the best sound quality in venues designed for amplified music, reverberation should be well controlled, though without the acoustics becoming excessively dry. Alongside appropriate sound-system design, this will help to ensure that the ratio of direct to reverberant sound is kept high, allowing for the delivery of a clear mix to the audience. Published advice on suitable reverberation-
time targets is available for venues of different sizes. Of critical importance to sound quality is the adequate control of reverberation at low frequencies (in the 125 Hz octave band especially).

Reverberation time can be reduced at mid-to-high frequencies through the introduction of porous absorption (e.g. heavy textiles, soft furnishings, dedicated wall or ceiling panels). An audience is itself a significant absorber of sound at mid-to-high frequencies. The control of reverberation time at low frequencies is more challenging and generally requires the use of resonant absorbers, which again can be wall or ceiling mounted. Resonant absorbers can also be used to tame room modes, which can otherwise cause an uneven low-frequency sound distribution in small venues such as bars or cafes. Sound diffusers are an alternative form of acoustic treatment which help to promote an even distribution of sound, and which can be used to solve specific acoustical problems, such as a strong reflection off the rear wall of a venue. A competent acoustician will be able to advise on the most appropriate treatment for a given venue.

Especially in venues that are highly reverberant to begin with, introducing sound-absorbing treatment to bring the reverberation time down will directly reduce sound levels, as well as making it easier for the sound engineer to deliver a controlled mix. Making the stage surroundings absorbent can help to control on-stage sound levels, as well as reduce stage spill into the audience area. However, if the stage area is made too dry, this will be detrimental to the musicians’ experience, so a balance is required.

Sound-system design
A key principle for achieving uniform sound distribution is to avoid a situation where some audience members are located much closer to the loudspeakers than others. Common solutions include elevating the main loudspeakers above head height and, where necessary, introducing delay loudspeakers further back from the stage to support sound delivery to the rear of the audience. Delay systems have proven effective not just at large-scale outdoor events, but also in challenging indoor venues with a deep audience area and low ceiling height.

If the distance ratio between the nearest and furthest listeners from a loudspeaker is not too great, loudspeaker directivity can be exploited to compensate for the natural attenuation of sound that occurs with distance. Loudspeaker directivity can also be exploited to help maintain a high ratio of direct to reverberant sound in indoor venues, by directing sound towards the audience and away from the walls and ceiling.

A near-ubiquitous design in modern-day sound reinforcement is the variable-curvature line array. Line arrays have good directivity control in the vertical plane and excellent ability to “throw” sound towards more distant audience areas. Line arrays are not the most suitable choice for all venues though, and the key consideration is to choose the most appropriate system to suit a given space. This process is greatly aided by the use of software packages which can predict sound levels throughout the audience area for different loudspeaker configurations.

With careful design, subwoofer arrays can be set up to project low-frequency sound towards the audience while minimizing propagation towards noise-sensitive areas (e.g. the stage). There is evidence that flown subwoofer systems are capable of achieving more uniform low-frequency sound distribution from front-to-back of an audience at large-scale events. However, the use of flown subwoofer systems remains rare at present, due in part to the practical challenges of rigging these large and heavy loudspeakers.
Coherent interference between loudspeaker systems placed on either side of the stage can give rise to substantial variability in low-frequency sound levels across the horizontal extents of the audience. However, electronic solutions are available to minimize this effect by decorrelating the signals sent to the left and right loudspeakers.

Where acceptable to the performers and within the means of a venue, the use of personal in-ear monitoring is recommended in place of traditional monitor loudspeakers. Removal of the monitors can substantially reduce on-stage sound levels and consequently stage spill to the audience area. With the sound engineer no longer having to compete with sound from the stage monitors, in small venues this may also make it possible to reduce the output of the main PA system, helping to reduce exposure for all audience members.

The art of the possible
There is little published literature directly evaluating whether adoption of the sort of room-acoustic and electroacoustic design principles identified in this report is effective at reducing audience sound exposure. However, a case study from Sweden offers promise that it is possible, through reasonably simple and straightforward steps, to tackle excessive sound exposure even in the challenging case of a small, indoor rock club.

Sandell et al. (2007) described the comprehensive acoustic renovation of an existing venue, which involved both treatment to improve the venue’s acoustics and a redesign of the PA system to achieve more uniform sound distribution. The results of the renovation surpassed the expectations of the multi-stakeholder group responsible for carrying it out. Stage spill to the audience area and sound-level variability throughout the venue were reduced. Most importantly of all, sound levels measured at the most-exposed audience location were consistently below the government-recommended 100 dB $L_{Aeq}$ limit, whereas prior to the renovation the levels had been close to 110 dB $L_{Aeq}$. 
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Appendix I: Details of reverberation time and drum-kit sound pressure level calculations

This appendix details the calculation of reverberation time and drum-kit sound pressure levels associated with the illustrative example depicted in Figure 3 of the report.

Room dimensions

Length: 10 m Room volume: 280 m$^3$
Width: 7 m
Height: 4 m

Reverberation time (RT60) calculations

Without treatment (corresponding to Figure 3a)

<table>
<thead>
<tr>
<th>Surface description</th>
<th>Area (m$^2$)</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
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<td>0.10</td>
<td>4.62</td>
<td>0.06</td>
<td>2.77</td>
<td>0.05</td>
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<td>2.72</td>
<td>0.03</td>
<td>4.08</td>
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<tr>
<td>Audience (standing)</td>
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<td>4.85</td>
<td>0.44</td>
<td>10.16</td>
<td>0.95</td>
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Sabins: 19.19 21.22 31.84 38.97 40.33 40.27

RT60 (s)$^3$ 1.39 2.12 1.42 1.16 1.12 1.12

With treatment (corresponding to Figure 3b)

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<tr>
<th>Surface description</th>
<th>Area (m$^2$)</th>
<th>125 Hz</th>
<th>250 Hz</th>
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<td>46</td>
<td>0.10</td>
<td>4.62</td>
<td>0.06</td>
<td>2.77</td>
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<td>Audience (standing)</td>
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<td>4.85</td>
<td>0.44</td>
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<td>Plush curtain, deeply folded (end wall)</td>
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Sabins: 32.46 41.55 68.45 77.61 77.78 79.09

RT60 (s)$^3$ 1.39 1.08 0.66 0.58 0.58 0.57

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1 Absorption coefficient (material and frequency dependent)
2 Total amount of absorption provided by a surface in Sabins = surface area x absorption coefficient
3 Reverberation time RT60 in seconds = 0.161 x room volume / total amount of absorption provided by all room surfaces (Kuttruff, 2009)
**Acoustic drum-kit sound power levels**

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<th>Octave-band centre frequency (Hz)</th>
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<th>160</th>
<th>200</th>
<th>250</th>
<th>315</th>
<th>400</th>
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<th>630</th>
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<th>3150</th>
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<td>105</td>
<td>112</td>
<td>107</td>
<td>104</td>
<td>100</td>
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<td>Octave-band Lw (dB)</td>
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<td>105.1</td>
<td>102.8</td>
<td>99.6</td>
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¹ Sound power level data are from Granzotto and Ruggeri (2010), Figure 11

**Diffuse-field sound pressure level calculations**

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<td>113.7</td>
<td>107.4</td>
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**Without treatment (corresponding to Figure 3a)**

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<thead>
<tr>
<th>Equivalent absorption area (m²)</th>
<th>19.2</th>
<th>21.2</th>
<th>31.8</th>
<th>39.0</th>
<th>40.3</th>
<th>40.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffuse-field SPL (dB)¹</td>
<td>99.9</td>
<td>106.4</td>
<td>98.4</td>
<td>95.2</td>
<td>92.8</td>
<td>89.6</td>
</tr>
<tr>
<td>Diffuse-field SPL after A-weighting (dB)</td>
<td>83.8</td>
<td>97.8</td>
<td>95.2</td>
<td>95.2</td>
<td>94.0</td>
<td>90.6</td>
</tr>
</tbody>
</table>

**With treatment (corresponding to Figure 3b)**

<table>
<thead>
<tr>
<th>Equivalent absorption area (m²)</th>
<th>32.5</th>
<th>41.6</th>
<th>68.4</th>
<th>77.6</th>
<th>77.8</th>
<th>79.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffuse-field SPL (dB)</td>
<td>97.6</td>
<td>103.5</td>
<td>95.1</td>
<td>92.2</td>
<td>89.9</td>
<td>86.6</td>
</tr>
<tr>
<td>Diffuse-field SPL after A-weighting (dB)</td>
<td>81.5</td>
<td>94.9</td>
<td>91.9</td>
<td>92.2</td>
<td>91.1</td>
<td>87.6</td>
</tr>
</tbody>
</table>

¹ Diffuse-field SPL = Sound power level – 10 x log₁₀(equivalent absorption area) + 6 dB (Kuttruff, 2009)

**References**
