Perception of Low Frequency Content of Amplified Music in Arenas and Open-air Music Festivals.

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Electronics

December 2016

Abstract

The purpose of this study is to investigate whether audience perception at large arena shows and music festivals can be improved by the addition of Infra-sub. Infra-sub refers to low frequency audio content below 50Hz, and its presence might help provide a more involving and engaging audience experience at lower sound pressure levels.

Historical aspects of the development of sound reinforcement technology within the live music industry are outlined. Concerns about the environmental effects of loud music, its social impact and associated health implications, as well as the increase in legislation around its presentation are all considered. A review of current knowledge regarding human perception of low frequency sound, both aurally and through other forms of mechanosensation is also presented.

This thesis investigates whether an increase in low frequency content (below 50Hz), both in terms of magnitude and frequency range, affects a listener's preferred listening level. The study was conducted in real-life situations at a number of European indoor arenas using a large format line array system with low frequency extension. The research shows that preferred listening levels were lower when low frequency content (Infra-sub) was increased. The implication of this result is that increasing Infra-sub content allows the environmental impact of large arena concerts and music festivals to be reduced whilst maintaining a positive listening experience.

The study had some limitations in sample size and range of participants. Future research will study the individual effects of range extension and increased sound pressure level at low frequencies, and their perception by the listener. Nevertheless, this study underlines the beneficial social, environmental and health implications of the use of Infra-sub, stemming from the overall reduction in sound pressure level at arena concerts and open-air music festivals.

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Acknowledgements

Firstly I would like to thank my wife, Rachell, for supporting my study for the last two years and tolerating my obsessions for over twenty. I would like to thank my supervisor, Jude Brereton, for her unstinting support and encouragement, and for dispelling the word 'this' from my vocabulary. I would like to thank Sid Rogerson for all his patient assistance when testing, as well as John Fairs and The Prodigy for indulging my bass experimentation. I would also like to thank Jason Baird of Martin Audio for his help in the prototype bass experiment 8 years ago. Thanks also to all at D&B and Vanguardia. I would also like to thank Jez Wells and Damian Murphy, friends and colleagues and everyone in the Audio-lab who have pitched in with help and suggestions without fail.

Declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

Statement of Ethics

Ethical approval was gained for all the listening tests undertaken via the Physical Sciences Ethics Committee (PSEC) of the University of York (November 2015).

1 Introduction

The profession of the live sound engineer has evolved in recent years with the rise in popularity, since around the year 2000, of the commercial open air music festival [1]. Live music revenues in 2012 almost matched those of recorded music in terms of gross value added and in 2013 exceeded them [2]. Festivals have begun to dominate the touring market and for many acts they increasingly form the backbone of their touring calendar. The move from primarily theatre based touring to open air shows has brought with it many acoustic problems. One specific problem is that of providing an 'involving' sound, one that engages and envelops the audience, making them feel part of the experience in an environment that is comparatively free of reflective surfaces and therefore reverberant sound. The physical scale of outdoor shows, and large arenas, places the listener, potentially further from the performer, and any primary sound source, than in a theatre or club [3]. The lack of walls and ceilings to reflect the sound, and provide a sense of 'space', an important feature of a theatre or concert hall auditorium, presents many challenges to the sound engineer in an open air environment. As Griesinger [4] notes;

"In the best concert halls and opera houses low frequency sounds envelop the listeners". "When the acoustics produce envelopment, music has a living quality that is highly prized".

McCarthy [5] writing on sound reinforcement notes;

"the tonal character of our listening experience is composed of three parts: the direct sound waveform, copies of the waveform, copies of the waveform that arrive within the summation duration window, and copies that arrive outside the duration window. Unless we are in an anechoic chamber all of these factors will be present".

Loudspeakers can be considered an acoustic source that can be synchronised with other acoustic elements of a performance. Modern sound reinforcement systems have revolutionised large concerts. Speech intelligibility and musical clarity, the ability of all the audience to hear and understand speech, to follow the nuances of pitch, timbre, and rhythm in a coherent way, has greatly improved in the last fifty years [6], however recent surveys still indicate audience dissatisfaction with the sound at music festivals [7].

Increasing restraints on environmental noise have impacted sound pressure levels at concerts, and in particular open-air festivals;

"Large, loud, outdoor music events like this were almost unknown before the 1950s, and their rapid increasing popularity through the latter part of the 20th century has created a case of

conflicting requirements of different stakeholders which need to be balanced: "democracy for listeners"; success for organisers; avoiding nuisance for neighbours [8]*"*.

This dissertation attempts to address aspects of the audience experience, *"the democracy for listeners",* and suggest ways to improve the sound in arenas and at open air festivals.

2 Research Background

2.1 Modern Sound Reinforcement

Electro-mechanical sound systems have been around for only a relatively short time, in practical terms around 100 years. The work of Jenson & Pridham of Magnavox, and Western Electric in the United States, Marconi, Siemens and Tannoy in Europe were to revolutionise the way concerts were heard in the period between the First and Second World Wars [9]. However, it was developments during the 1960s that enabled large open air events to become a more viable proposition. Festivals such as the Isle of White Festivals of 1968-70 and Woodstock (1969) drew huge crowds and captured the public's imagination. The rise in festivals' popularity was to lead to a new wave of development in sound reinforcement systems suitable for events of this size.

Increasingly sophisticated sound reinforcement systems are now able to accurately reproduce sound with little of the spectral colouration or temporal smearing (see glossary) previously associated with sound systems using multiple drivers necessary for large audience coverage [10] (Figure 1). The use of delayed satellite speakers (Figure 2) has extended the possible audience area further, beyond the coverage of the main speaker system, whilst still retaining clarity (coherent and intelligible sound) as defined in ISO 3382 [11].

Figures 1 and 2 (produced using speaker manufacturer D&B Audiotechnik's 'Array Calc' prediction software [12]) show the even (+/-3dB) and predictable coverage obtainable with a modern line array, in this case the D&B J series [13] The area indicated is a flat field site 80 metres wide by 120 metres long. The colours indicate the predicted level at all points on the listening plane at a height of 1.7m. The colour scale is set to indicate sound pressure level (SPL) and each colour represents a difference, in these examples, of 3dB per division. Red is the highest SPL at 105dB and over, Dark Orange 102-105dB, Orange 99-102dB and yellow 96-99dB (See scale at side of Figures 1 & 2). The grey squares represent the speaker arrays and the stage area is marked to the left of the plot. The Front of House (FOH) mix position is just to the left of centre.

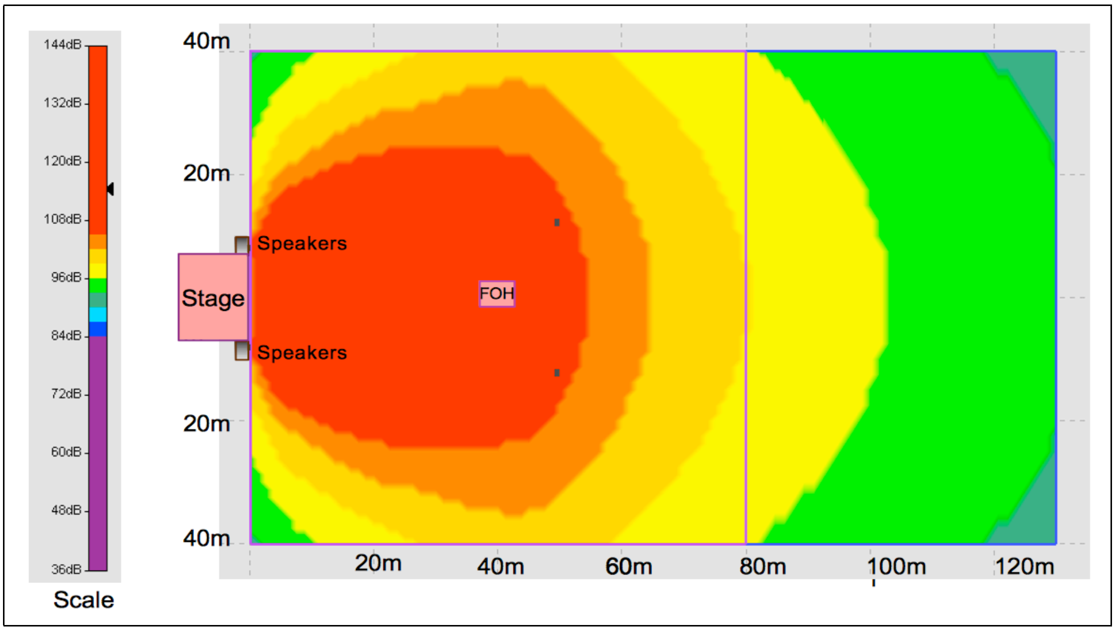

Figure 1: Festival speaker system in a 80m x 120m area showing coverage using Pink Noise in dB . Stage is marked in pink to the left of diagram, FOH mix position at 40m. Scale on left indicates SPL by colour (Prediction based on 12 D&B J-series line array cabinets per side, listening height 1.7m, resolution 1m, air absorption 24◦C/60% Humidity, Broadband Pink Noise).

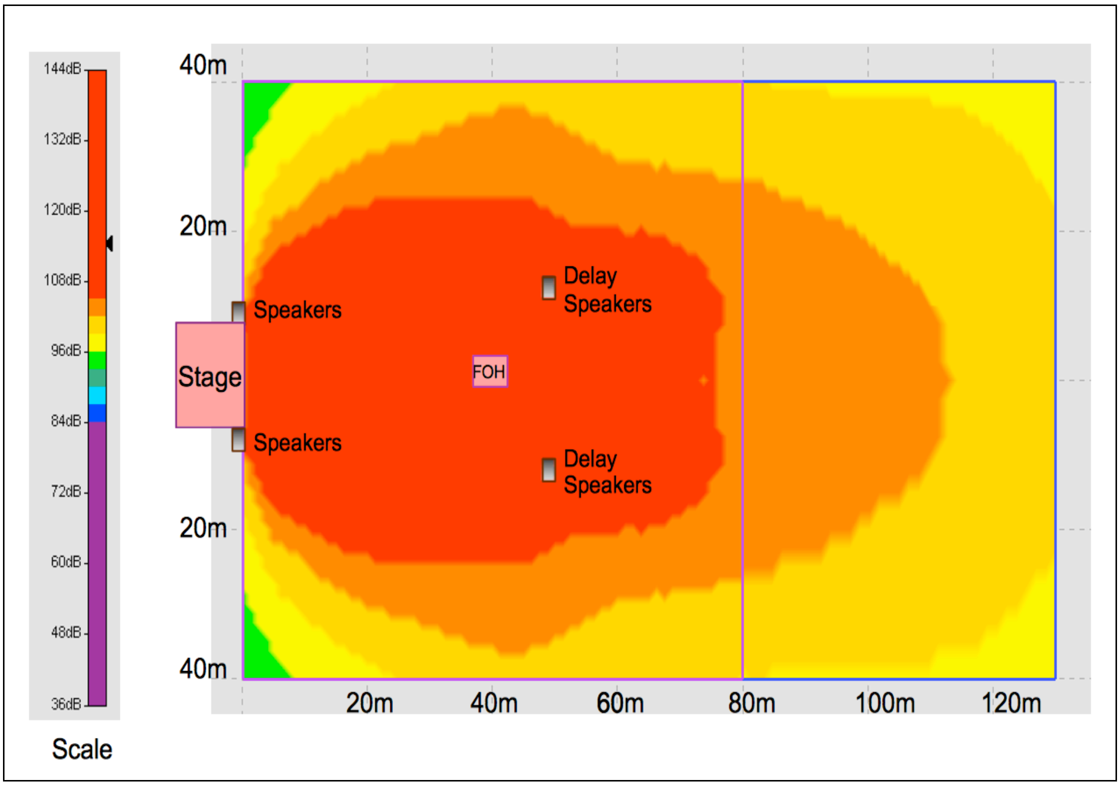

Figure 2:Festival speaker system with added delay speakers at 50m in a 80m x 120m area showing coverage using Pink Noise in dB SPL. Coverage has been extended from beyond 100m from the stage as seen by the increased red/dark orange colouring SPL. Stage is marked in pink to the left of diagram, FOH mix position at 40m. Scale on left indicates dB SPL by colour (Prediction based on 12 D&B J-series line array cabinets per side, listening height 1.7m, resolution 1m, air absorption 24◦C/60% Humidity, Broadband Pink Noise).

As the plot shows, the coverage radiates evenly from the stage to the audience area, producing a coverage variance of +/- 3dB. The signal represented is broadband pink noise (noise where the power spectral density (energy or power per Hz) is inversely proportional to the frequency of the signal, each octave band (halving/doubling in frequency) carries an equal amount of noise energy).

2.1.1. Line Array

Modern festival sound systems currently in use were developed largely through the work of Dr Marcel Urban and Christian Heil (which in turn is built on work by Olson in the 1940s [14]). Urban and Heil's development of line array systems in the 1990s was an effort to overcome the drawbacks of point source (see glossary) systems, where the deployment of multiple cabinets, sufficient to cover the large audience area, resulted in adverse comb filtering effects and uneven distribution (see section 2.1.5 for further discussion of this point) [3]. In the early 1990s Urban and Heil's work led to the commercial release of the L'Acoustics V'Dosc system. Discussing the problems of multiple source speaker systems in 1992 Christian Heil commented;

"The only means to solve these problems is to define criteria for array-ability, which, when achieved, allow the array to behave exactly like an equivalent single source having the same size as the array"[15].

The development of the Dosc waveguide and Wavefront Sculpture Technology [16] revolutionised modern public address speaker design, and the large format line array system was born. V'Dosc brought with it a greater clarity to large sound reinforcement systems [17]. Line array systems by L'Acoustics and other non-propriety systems by such as JBL [18], D&B Audiotechnik [19], Meyer Sound [20] and Martin Audio [21] now make up the majority of speaker systems at music festivals worldwide. Table 1 demonstrates the dominance of the modern line array system over other conventional systems, the data was taken from a cross section of well established European Festivals, with audience capacity on the main stage in excess of 15,000, in 2015.

Festival	Manufacturer	Speaker System Main Stage	Type
Rock im Ring, DE	L'Acoustic	K1	Line Array
Rock am Park, DE	L'Acoustic	K1	Line Array
Isle of White, UK	D&B Audiotechnik	J Series	Line Array
Parklife, UK	D&B Audiotechnik	J Series	Line Array
We Are Electric, NL	L'Acoustic	V'Dosc	Line Array
Tinderbox, DE	L'Acoustic	V'Dosc	Line Array
Werchter, BE	Adamson	E15	Line Array
Rockwave, GR	L'Acoustic	V'Dosc	Line Array
Nos Alive, PT	L'Acoustic	V'Dosc	Line Array
T in the Park, UK	L'Acoustic	V'Dosc	Line Array
Benicassim, Es	L'Acoustic	V'Dosc	Line Array
Glastonbury, UK	Martin Audio	MLA	Line Array

Table 1: Sample Cross section of Major European festival sound reinforcement systems 2015 (samples chosen from European festivals, established more than 5 years, with audience capacity on main stage >15k).

With the V'Dosc line array and its predecessors becoming more widely used in the latter half of the 1990s it became possible to have a speaker system that met the criteria for clarity, the ability of the listener to hear and understand speech, to follow the nuances of pitch, timbre, and rhythm in a coherent way, up to 90m without significant loss of frequency response and sound pressure level (SPL). Line arrays produce a loosely cylindrical wavefront that expands predominantly in the horizontal plane, doubling in area for every doubling of distance. This equates to an approximately 3dB loss every doubling of distance. In comparison a point source system radiates in a spherical wavefront that expands to four times the area every doubling of distance, equating to a 6dB loss every doubling of distance. The line array will however appear to behave as a point source the further you get from the array. Before this point, close to array, is referred to as the 'near-field' or 'Fresnel region', beyond that distance it is referred to as the 'far-field' or 'Fraunhofer region' [22]. A 5.4m tall line array has a near field region where the dB level drops at 3dB per doubling of distance of 88m [23]. A line array will maintain high frequency content over longer distances than an equivalent size point source array.

2.1.2. Delay Arrays

Secondary line array systems can be hung at a distance, typically 50m, from the main line array system to increase coverage area (See Figure 2). These 'delay arrays' receive an input signal identical to that sent to the main system, but that has been digitally delayed so that the sound sources are time aligned when measured from in front of the delayed array. Sound waves arriving from the main array will arrive at the secondary array at the same time as the delayed signal is produced in the secondary array. These sounds will then combine and increase the overall coverage of the sound system. With the use of delay arrays the distance and area covered by the sound system can be increased comfortably to several hundred meters, or more.

2.1.3. Speaker system design

Modern speaker systems employ electronic cross-over filters to split the audio signal into 'bass' 'mid' and 'treble' components. In a line array cabinet such as L'Acoustic V'Dosc these signals are the reproduced using the different components within the cabinet. Bass frequencies are reproduced with a pair of 15 inch drivers, the mid range by four 7 inch drivers and the high frequencies by a pair of 1.4 inch drivers [24]. The signal is split by electronic filters before the power amplifiers using electronic cross-over networks [25]. These divide the incoming signal and apply high and low pass filters to produce bandwidth limited signals typically in a three-way system in the ranges 0-250Hz (Low), 250 – 1500Hz (Mid) and 1500 – 20000Hz (High). V'Dosc is considered a 'three-way' system as the input signal is split up to be sent to the 3 sets of speaker components, each requiring separate amplification.

Although the V'Dosc line array system was originally conceived as full-range, covering all frequencies perceived as necessary for musical reproduction, it was felt by many sound engineers that, despite having a manufacturers stated frequency range from 50Hz to 18Khz, the range was still deficient [26]. The system was found to be producing insufficient SPL at low frequencies. Although theoretically the practical limit for low-frequency reproduction of the line array was lower than 50Hz, L'Acoustics adopted a 'four–way' system approach and developed the SB218 Subwoofer cabinet [27] to handle low frequencies . Designed to be stacked underneath the V'Dosc array, the SB218 subwoofer cabinet extended the lower frequency range of the system to around 30Hz.

One important innovative feature of the V'Dosc system was L'Acoustics insistence that all operators needed to be trained to their standards. Prior to this very few sound technician courses were available dedicated to live sound. L'Acoustics introduced Certified V'Dosc Engineers (CVE), who had undertaken rigorous training in the theoretical and practical application of the system. No system was allowed to be used without a qualified engineer supporting it. This helped educate users in not just the operation of the system, it's design and construction, but also the background acoustic theory behind it's application.

2.1.4. Reproducing Low Frequencies

As sound systems grew in size and sophistication, by the turn of the century an increasingly better educated generation of technicians began examining more closely the interaction of cabinets, and the ways large sound systems could be constructed . Although there still remain many opinions on how low frequency subwoofer cabinets should be deployed, they fall broadly into two main camps, 'Left/Right' and 'Central Array' as illustrated in Figures 3 and 7. Although both techniques have their advantages, for the majority of the audience, rather than a central listener, the central array is a more democratic option offering a more even SPL over the entire listening area.

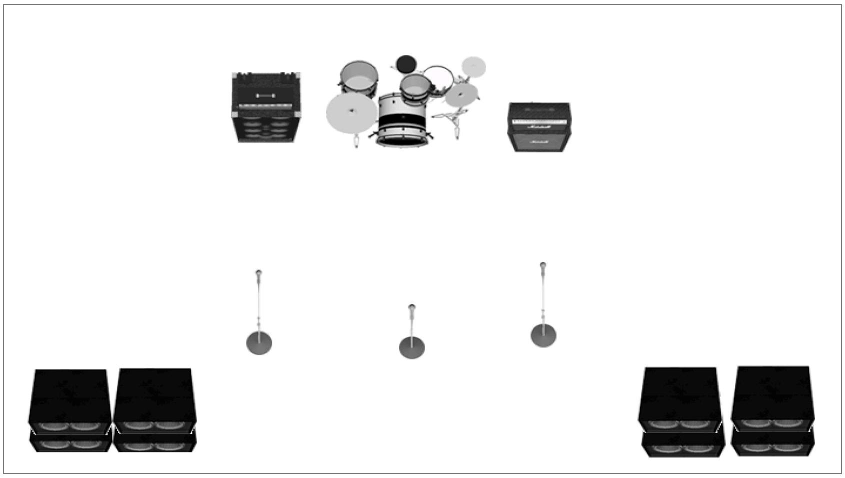

Figure 3: Left /Right stacked subwoofer cabinet. 8 Subwoofers are arrayed symmetrically either side of the stage.

2.1.5. Left/Right Sub Array

With multiple sound sources 'comb' filtering occurs. When the waveforms from two or more sound sources converge that are delayed slightly they will not combine exactly, but rather combine constructively or destructively dependent on frequency. The result when plotted on a response graph has a 'comb-like' appearance hence the name (Figure 4) .

In sound reinforcement comb filtering is most noticeable in lower frequencies and produces what is known as 'power alley'. Distinct corridors of low frequency sound can be heard with noticeable dips or 'troughs' either side. At higher frequencies these troughs are narrower and less noticeable. As the frequency drops the troughs become wider and more discernible, problem areas appearing to shift due to the differing widths. Figure 5 shows the SPL prediction of a 50Hz tone. The red bands represents the alleys of higher SPL flanked by troughs of much lower SPL. As most performances feature repetitive bass notes, often with instruments such as a bass drum at a constant pitch, comb filtering can produce a very mixed experience for the audience, depending on their location. As Bracusi [28] discusses in his article “The Power Alley”, some members of the audience will hear a summation, others will hear a cancellation of the two sources. Depending on the sound engineers mix position summation, or cancellation, can contribute to an unsatisfactory “mix” or balance of sound sources.

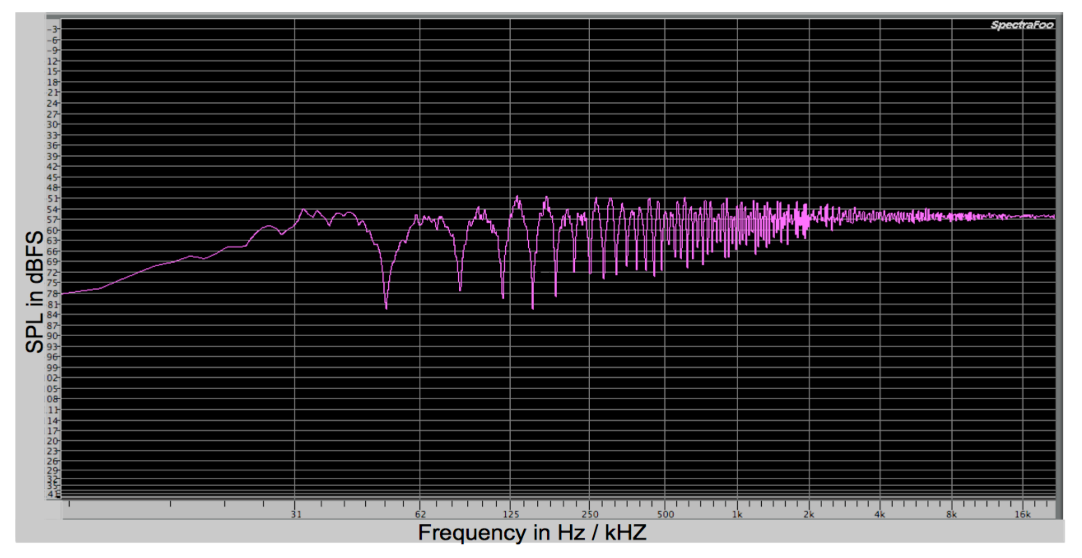

Figure 4: Two channels of identical pink noise combined but with the second channel delayed by 30ms. The Signal clearly shows the constructive and destructive effects of the combining of the signals and the 'comb' like pattern produced. The same signals combined with out delay when averaged over time would produce a nominally flat line.

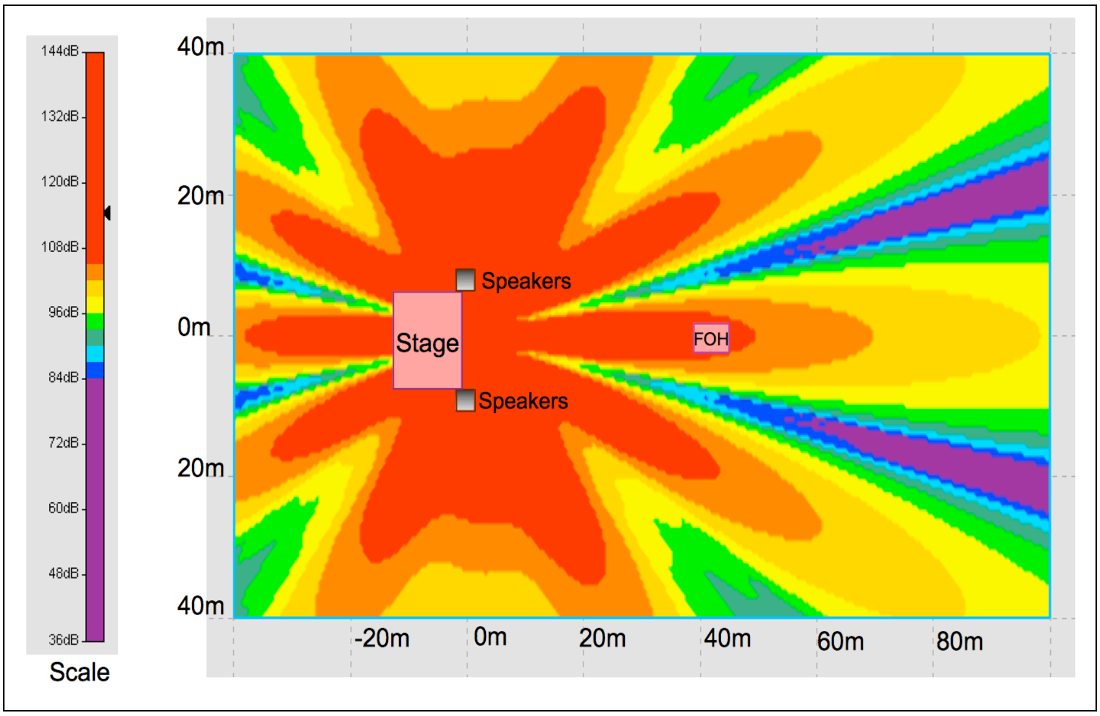

Figure 5: Left/Right Array: Plot showing predicted SPL levels at 50Hz of 8 subwoofers stacked equally to the left and right of the stage. Large dips in level can be clearly seen especially either side of the FOH mix position at 40m. The peaks are known as 'power alleys' where the sound will appear loud then quiet when traversed adjacent to the downstage edge (Prediction based on 4 x D&B B2 Sub Bass cabinets per side, listening height 1.7m, resolution 1m, air absorption 24◦C/60% Humidity @ 50 Hz).

2.1.6. Central/Broadside Array.

A central or 'broadside' subwoofer array can help overcome comb filtering produced by multiple sources (Figure 6 & 7) if the elements are close enough to one another, within two-thirds of a wavelength of the highest frequency produced [29]. Broadside arrays however suffer from several practical issues. Often it is not possible to physically place subwoofers in a line across the front of a stage due to the stage having an apron, seating or security issues, or obstruction of view. These problems are most associated with permanent structures such as theatres. On an open air festival show most of these are not issues, and cabinets can be arrayed along the downstage edge, having often been integrated in to the design of the temporary structure of the staging. Having subwoofer cabinets close to the stage centre can cause problems with bass frequencies being picked up by microphones onstage, as well as be off-putting for performers. The problem of rear spill can be partially overcome by using a cardioid subwoofer array as discussed by Hill, Hawksford, Rosenthal and Gand [30].

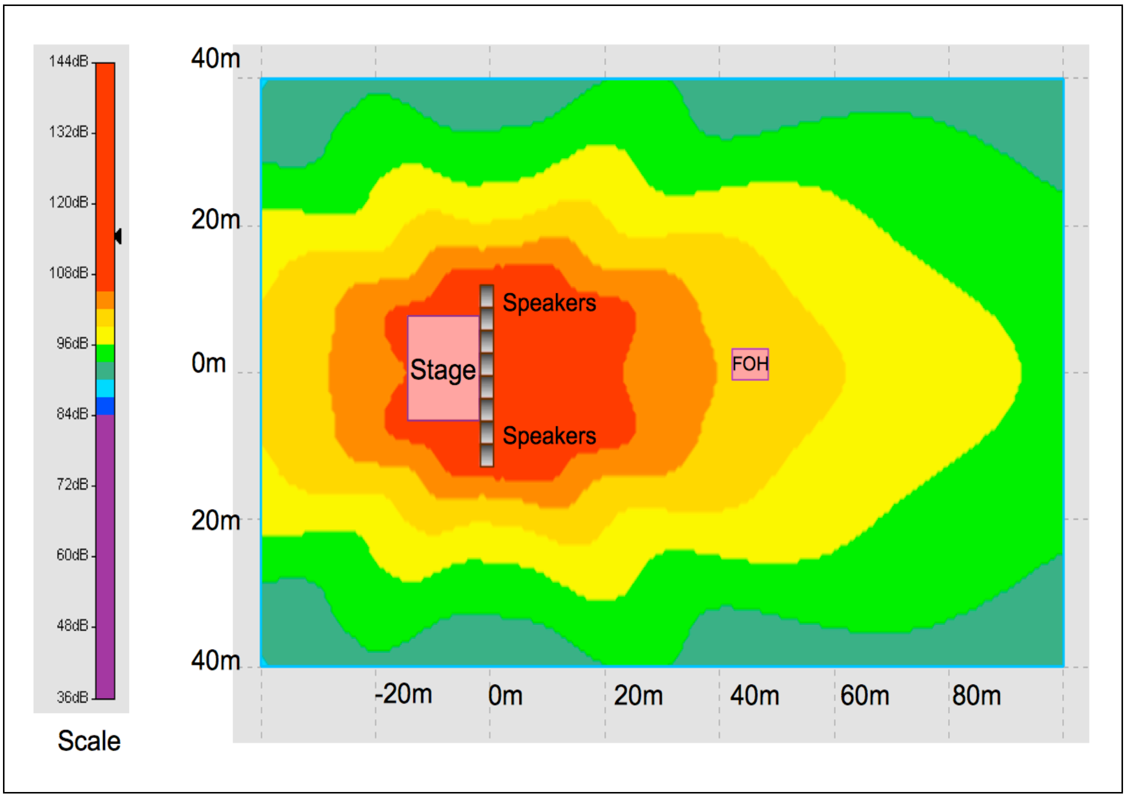

Figure 6: Central/Broadside Array: Plot showing the even coverage produced by Broadside array (Prediction Software based on 8 x D&B B2 Subwoofer cabinets arranged in straight array, listening height 1.7m, resolution 1m, air absorption 24◦C/60% Humidity @ 50Hz).

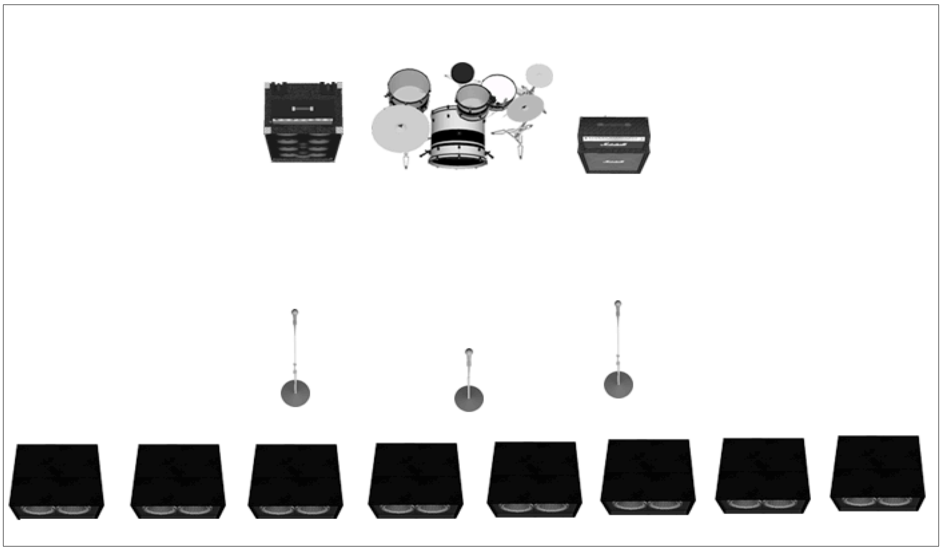

Figure 7: Centrally Arrayed Subwoofers. 8 Cabinets are arrayed equally spaced along the downstage edge central to the stage centre.

2.1.7. Cardioid Subwoofer Array

A cardioid subwoofer or gradient array works by introducing a second sound source at a defined distance from the main source. The back speaker is delayed equal to the time-of-flight distance from the front speaker and polarity inverted. The progression of wave from the front speaker in the forward direction matches that of the rear wave of the back speaker. The inverted negative peak of the back speaker matches the positive peak from the front speaker, it is 180 degrees out of phase and out of polarity. The signals combine producing 6dB more than their individual waves. In the reverse direction, at the rear of the cabinet, the waves from the front and back speaker are in opposite polarity. The closer they come to becoming in phase the greater the degree of cancelation. The sound energy radiated to the rear is therefore considerably less than that from the front of the cabinet (Figure 8). For a cardioid speaker system to work effectively the sound path length from the rear source to the front has to be in the magnitude of a quarter of the wavelength desired. To achieve cancellation, phase and level of the rear source need to be aligned by their own separate signal process and amplification. This technique will only work for a small bandwidth, about an octave, as wavelength varies with frequency and the distance between the sources remains constant. There is also some loss of SPL compared to a conventional system utilising the same number of components. The resulting dispersion is a cardioid (heart shaped) polar pattern with greatly increased directivity (Figure 9). Cardioid Subwoofer Array (CSA) techniques can help decrease the problems of onstage noise as well as environmental problems to the rear of the stage (Figure 11), but can have issues with changes to the impulse and consequently frequency response of the array. This can be perceived as temporal and spectral distortion as seen by Shabalina, Ramuscak & Vorlander [31].

Several manufacturers, e.g. D&B Audiotechnik and Nexo, produce dedicated CSA cabinets which, although they require multiple channels of amplifiers, can significantly improve directivity and rear rejection at low frequencies in an easy to use stand-alone unit.

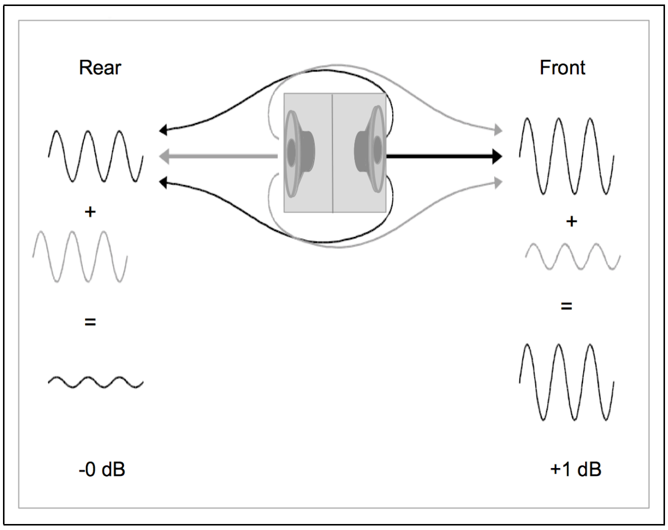

Figure 8: Diagram of a cardioid subwoofer cabinet. Energy from the rear facing speaker cancels out the near omni directional output of the front speaker to produce a significantly lower rear level. The overall effect is to produce a cardioid output at the desired frequency dictated by the magnitude of the wavelength.

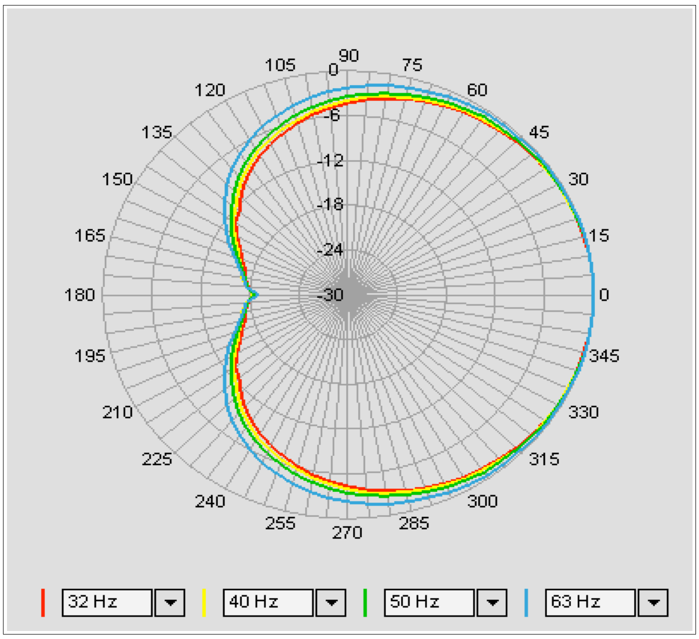

Figure 9: Polar pattern for a D&B Audiotechnik J series J-Infra Subwoofer cabinet. The dispersion is clearly forward facing (from left to right) and cardioid (heart shaped).The pattern is also maintained across the frequency range of the device as indicated by the different coloured plots.

Both the standard broadside and cardioid subwoofer arrays coverage suffer from a lack of width. Coverage can be widened by adding delay to the signal source to each cabinet increasing from the centre to the ends of the array. The delayed cabinets form a 'virtual arc' with the sound radiating concentrically from the array (Figure 10 & 11).

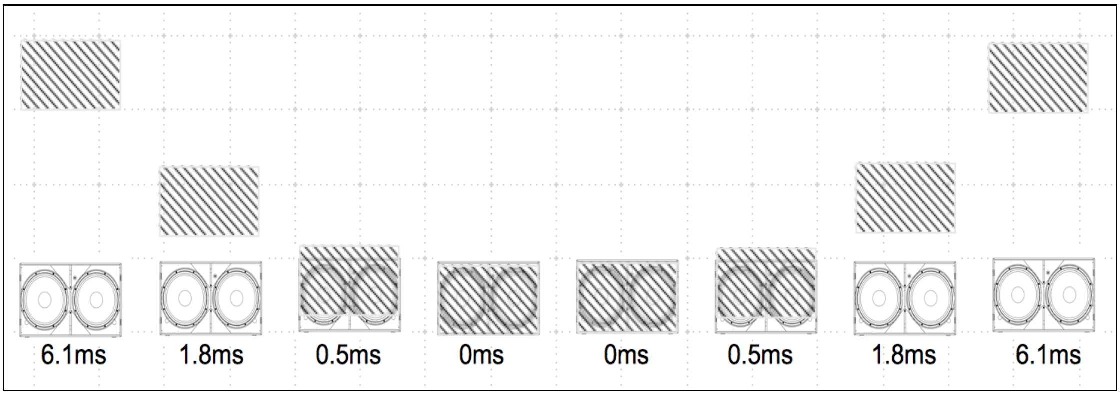

Figure 10: Delayed Broadside Array: diagram demonstrating the use of delay (marked below the cabinet in milliseconds) on individual cabinets to create a virtual arc. The shading indicates where the cabinets virtual source appears to be, the line diagram the actual cabinet position. Example coverage can be seen in Figure 11.

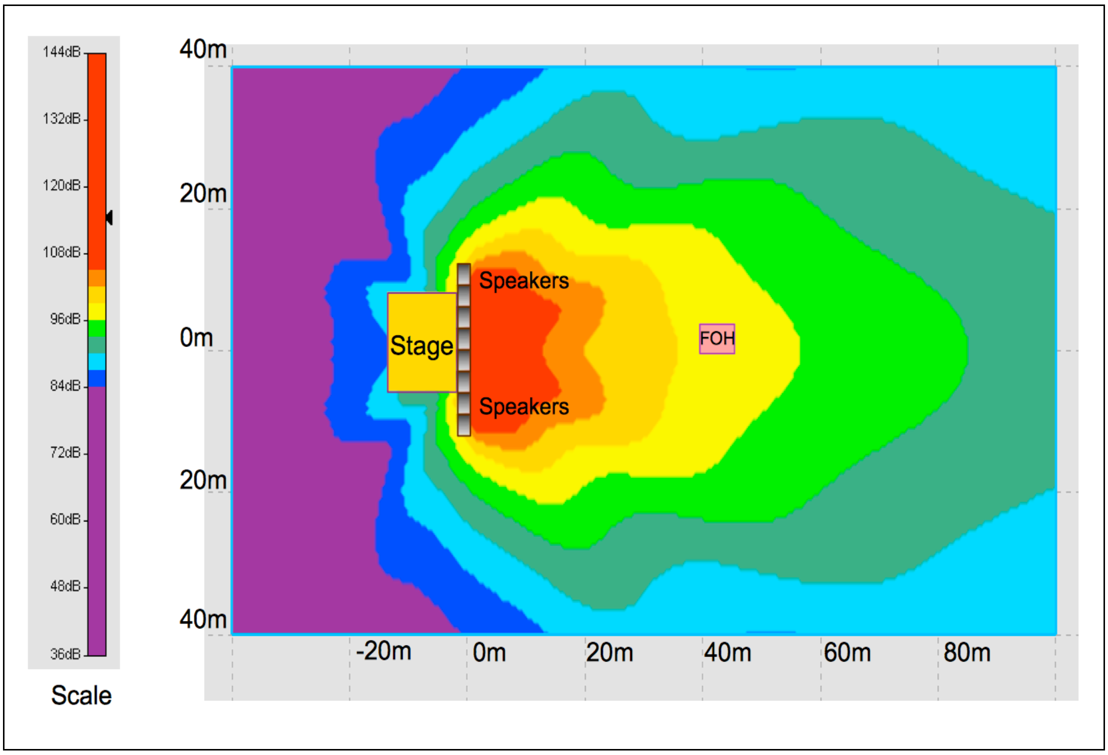

Figure 11: Cardioid Array: Plot showing the even coverage produced by a Delayed Broadside array using cardioid Subwoofer cabinets. (Prediction Software based on 8 J-series Subwoofer cabinets, in a delayed broadside array, listening height 1.7m, resolution 1m, air absorption 24◦C/60% Humidity @ 50 Hz)

2.2 Environmental Noise

Environmental noise pollution has become an ever growing problem [32] and legislation introduced to regulate its effect now increasingly dictates the ambient sound pressure level (SPL) acceptable not only in the work place, but in our daily lives. This is now increasingly true at most open air festivals in Europe. Founder of British pioneering public address company WEM, Charlie Watkins, recollected of his early festival experiences;

"*I felt a hand on my shoulder and heard the words: 'I must ask you to accompany me to the police station.' There he was, this policeman, with the Lord Mayor in all his robes, the residents' committee, the Noise Abatement Society... It was bloody ridiculous, particularly as there were people leaning out of the houses nearby, cheering and waving!" Charlie Watkins, Windsor Blues Festival 1967* [*33*].

Since Watkins provided his sound systems in the 1960s, equipment, and regulations, have advanced. The Government's current 'Noise Policy' [34] and 'Control of Noise at Work Regulations' [35] dictate the level of on-site and off-site noise. At most festivals these levels are enforced based primarily on SPL readings taken at the front of house (FOH) mix position.

2.2.1. Sound Pressure Level Measurement

The SPL reading for environmental noise regulation is typically taken between 30 – 40m from the downstage edge at the FOH mix position. The measurements are averaged over a set time period, normally fifteen minutes, and represented as an equivalent continuous noise level (Leq). Leq measurement is normally obtained using the 'A' weighted setting on the noise measurement meter (LAeq level). 'A' weighting, which is commonly used for environmental and industrial noise measurement, is covered in greater depth in section 2.2.2.

UK festivals will normally be given off-site target SPL levels with which to comply. An on-site level will then be set that correlates to these off-site levels. This is used to maintain the level below the off-site target. Prescribed LAeq SPL targets will then be set for sound engineers to comply with during the performance. The SPL is then monitored periodically on and off-site. The crucial measurement is the off-site level, usually taken at the outside of the nearest dwelling. The Noise Councils 1995 'Code of Practise on Environmental Noise Controls at Concerts' recommended that music noise levels (MNL) should not exceed 65dBA over 15 minutes at 1 metre of the facade of the nearest noise sensitive premises [36]. The recommended onsite level will then be calculated as can be seen in this recommendation from the licensing application of Glastonbury Festival, UK.

'At all stages, a target sound level of LAeq, 15 minutes 98dB at the front of house should be adopted." - *Glastonbury festival noise statement of intent 2007-10* [37]

Regulations governing SPLs are being introduced across Europe with other countries adopting either regional or National polices. Kok [38] notes that several countries in Europe have adopted levels based on the Swiss rules for music events which specify on-site measurement SPLs:

"*The sound emissions are limited to such an extent that the emissions do not exceed the hourly level of 100 dB (A)*" [39].

The Swiss on-site SPL is lower than an audience could normally expect in an auditorium where levels in excess of 100dBA are not uncommon. Although data on actual noise levels at non-regulated concerts is not widely available a comprehensive study was made by Griffiths in 1991 for the UK Health and Safety Executive [40] and a more recent study published in 2007 is available online [41].

Table 2 shows data gathered by Griffiths [37]. The sound pressure level was measured at the audience position at the front of the stage. As can be seen in Table 2, in the music genres Rock, Pop, Rap and House the mean LAeq exceeds 105dB, with over half the concert being above 104dBA in each case. It is only in the 'middle of the road' genre (MOR) that the level is below 100dBA.

Concert Type	LAeq				
	Sample Size	mean	range	SD	% above 104dBA
All concerts	18	104.7	94.4 – 113	4.7	61
Rock	7	106.1	102.9 – 109.9	2.6	86
Pop	5	105.9	101.6 – 113	4.5	60
MOR	3	97	94.4 – 98.8	2.5	0
Rap	2	107.4	102.8 – 112	6.5	50
House	1	106			above

Table 2: SPL measured at the front of the stage by Griffiths (1991) showing the mean SPL of 5 musical genres. MOR indicates 'middle of the road' traditionally a quieter musical form. SD indicates Standard deviation. As can be seen the mean of the total sample was 104.7 with 61% of the concert being above that level [37].

Lower SPLs introduced at European festivals such as Glastonbury (compared to those based on the levels in Table 2), combined with the lack of a naturally reverberant space, could be perceived as quiet and less involving. Working with a fixed ceiling to the SPL can also be constricting as it reduces the available dynamic range between the background noise of the crowd, surrounding stages, other amusements, and the prescribed SPL.

2.2.2. Perception and Weighting.

Noise measurements at festivals made by local council officers, or independent specialist companies, are usually over set time periods, usually between ten and fifteen minutes using the A-weighted scale (LAeq) (Figure 12). Off-site sound pressure levels are usually between 40 –

60dBA. The A weighted scale is based on the Fletcher and Munson 40 phon equal loudness curve which equates to a level of 40dB at 1Khz. The A-weighted off-site SPL dictates the overall show SPL, rather than the SPL at the FOH mix position. The A-weighted scale is based on the loudness curves set out in the following international standard: IEC 61672-1:2013 [42]. This scale represents the relative loudness of different frequencies perceived by the human ear at lower SPL [43].

The C-weighted scale, which is more appropriate for the higher SPL found at FOH mix position, is occasionally cited but rarely used as the primary measurement standard, as it is difficult to correlate to the A-weighted level used for the more important off-site measurement. Z-Weighting represents a non weighted flat response but is primarily used for testing purposes, such as frequency response, rather than the effect sound has on people, so is not used for environmental monitoring purposes. The weighted scales differ particularly in low frequency content as can be seen in Table 3 and Figure 12:

Frequency (Hz)	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**
A-weighting (dB)	*-26.2*	*-16.1*	*-8.6*	*-3.2*	*0*	*1.2*	*1*	*-1.1*	*-6.6*
C-weighting (dB)	*-0.8*	*-0.2*	*0*	*0*	*0*	*-0.2*	*-0.8*	*-3*	*-8.5*
Z weighting (dB)		*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*

Table 3: Comparison between A,C and Z weightings at spot frequencies. Although all are equal at 1kHz, the C and and A weighted curves drop off at lower frequencies, the A-weighted more dramatically.

In Table 3 it is noted that the 63Hz octave band A-weighted measurement is 26.2dB lower than the flat Z-weighted measurement, which can also be seen in Figure 12. Energy in the frequency range 1kHZ to 6.3KHz contributes more to the overall LAeq. Reinforcing low frequencies to take advantage of the low frequency roll-off, as a way to increase the overall perceived level, in relation to the A-weighting is investigated in this study.

2.2.3. The Rock & Roll Level.

In his influential paper 'Hearing Loss and Music' [44] Ken Dibble recounts the introduction in 1973 of a 96 dB (A-weighted) noise level (taken at an unspecified point inside the venue) in the City of Leeds as part of it's 'Music, Singing & Dancing License' following a report commissioned by its Department of Architecture [45], which resulted in a total decline of popular music in the city. It was revised following a further independent report commissioned by the Association of Ballrooms [46] combined with the weight of negative public opinion. Although acceptable levels for music are currently a matter of debate, most festivals operate at between 98dBA and 100dBA, measured over a 10 minute period at the FOH mix position. A

Study of the Swiss Paleo Festival at Nyon states that the level of 100dBA was a *"Good compromise between the public health issue, the demands of artists and organisers, and the expectations of the public"* [47].

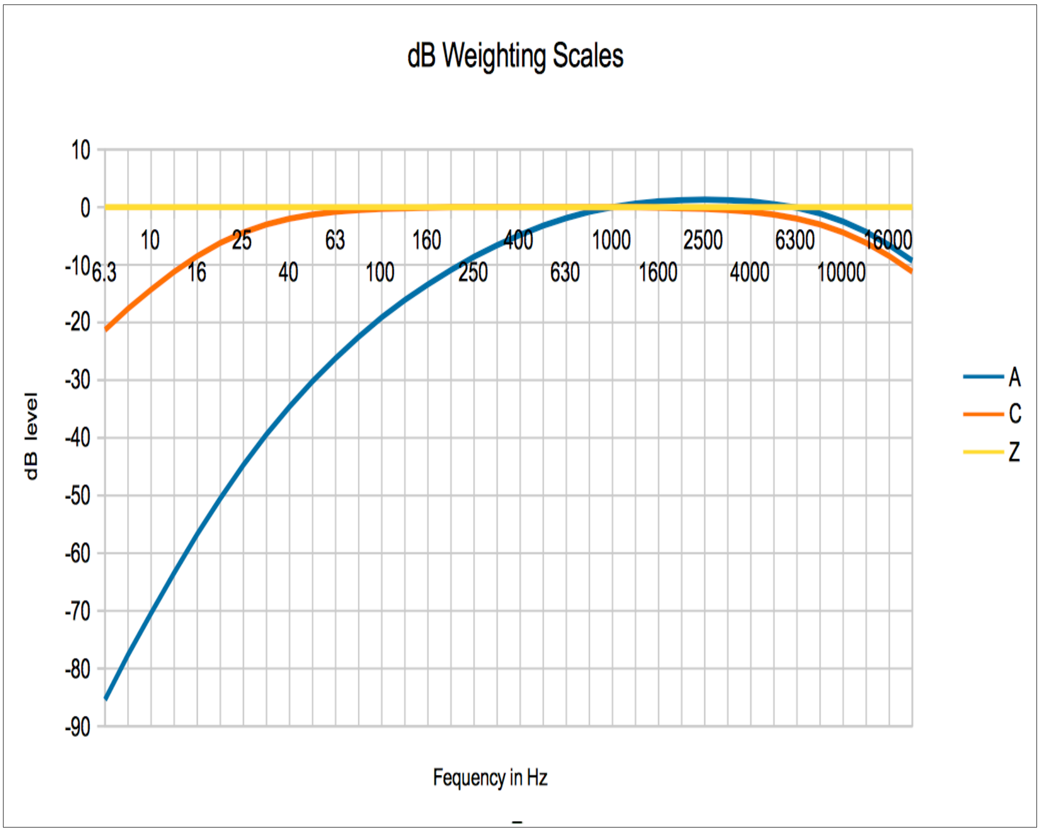

Figure 12: Graph illustrating the curves at different frequencies of A,C and Z weighting. The Z weighting showing a flat response, the C weighting a gentle high and low frequency roll off and the A weighting a large roll off at low frequencies, slight boost in the upper mids and more gentle High frequency roll off than the C weighting curve [42].

2.3 Musical Content

The spectral content of music differs from genre to genre, with the instrumentation used having an effect on the frequency range utilised and the dynamic range it is capable of producing. As Meyer notes in his “The Sound of the Orchestra” any musical genre featuring percussion or brass instruments is capable of producing very high SPL [48]. Popular music utilises brass and in particular percussion, in the form of the drum kit. The sound of the drum kit can often dictate the overall level of sound on stage. The drum kit can produce an average onstage SPL of 105dB with peaks of 144dB [49]. This research project focuses on popular music at music festivals.

2.3.1. Low Frequencies

Dayal and Ferringo note that, of the modern popular musicals styles, electronic dance music (EDM) has the greatest amount of low frequency content [50]. Spectral analysis of recent releases in the EDM genre shows a good deal of low frequency content. Figures 13 -17 are spectrograms taken from a variety of artists and a mix of genres.

In each spectrogram the horizontal axis represents a logarithmic frequency scale. The vertical axis represents time from 0 seconds (top) – 30 seconds (bottom), the duration of each capture. Red represents the greatest amount of energy at a particular frequency, and black no discernible energy at that frequency. The scale represents decibels relative to full scale(dBFS) (see glossary)). The frequency range has been limited from 8 – 2500Hz to better display the lower frequencies. The majority of the low frequency content is generated by percussion instruments, although with the more contemporary music (Figures 13 & 15) synthesised sounds can contain very low frequencies, and are increasingly used to provide bass lines as well as percussion parts.

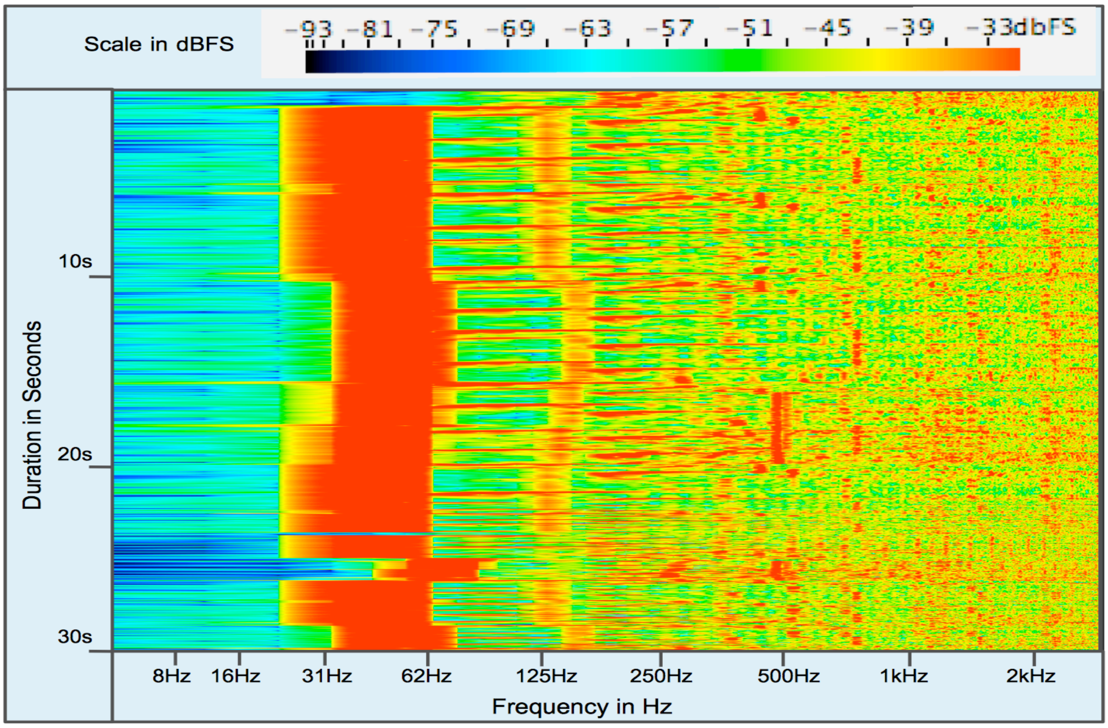

Figure 13: Spectrogram of Chase & Status 'No Problem' (EDM). The thick red banding represents the prominent bass line produced using a synthesized sound source. Percussion sources can clearly be seen extending below the bass line showing significant energy below 16Hz. (Spectrogram produced using Spectrafoo with 30 second sample time, frequency scaled from 4 – 2500Hz, 1024 Pt Hanning Window at 44.1kHz giving frequency resolution 43Hz.

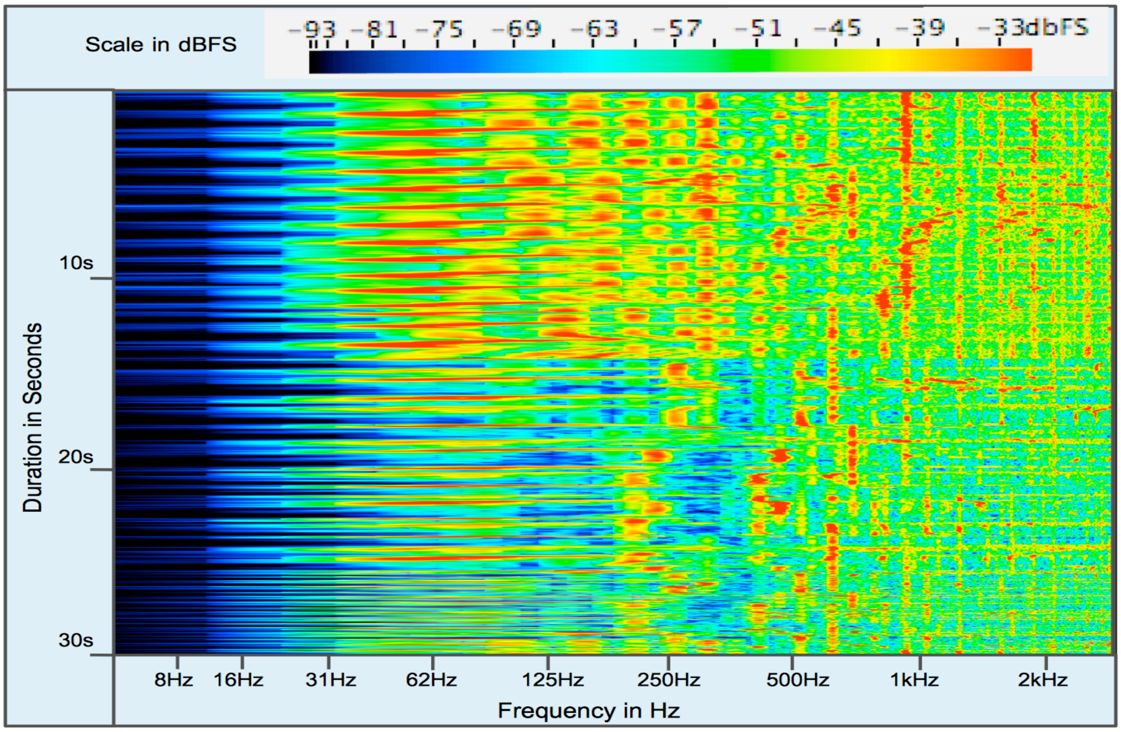

Figure 14: Spectrogram of Katy Perry "Fireworks" (Pop). The bass line is less prominent than in Chase& Status but the use of synthesised drums increases the low frequency range to below that of a conventional bass drum.(Spectrogram produced using Spectrafoo with 30 second sample time, frequency scaled from 4 – 2500Hz, 1024 Pt Hanning Window at 44.1kHz giving frequency resolution 43Hz.

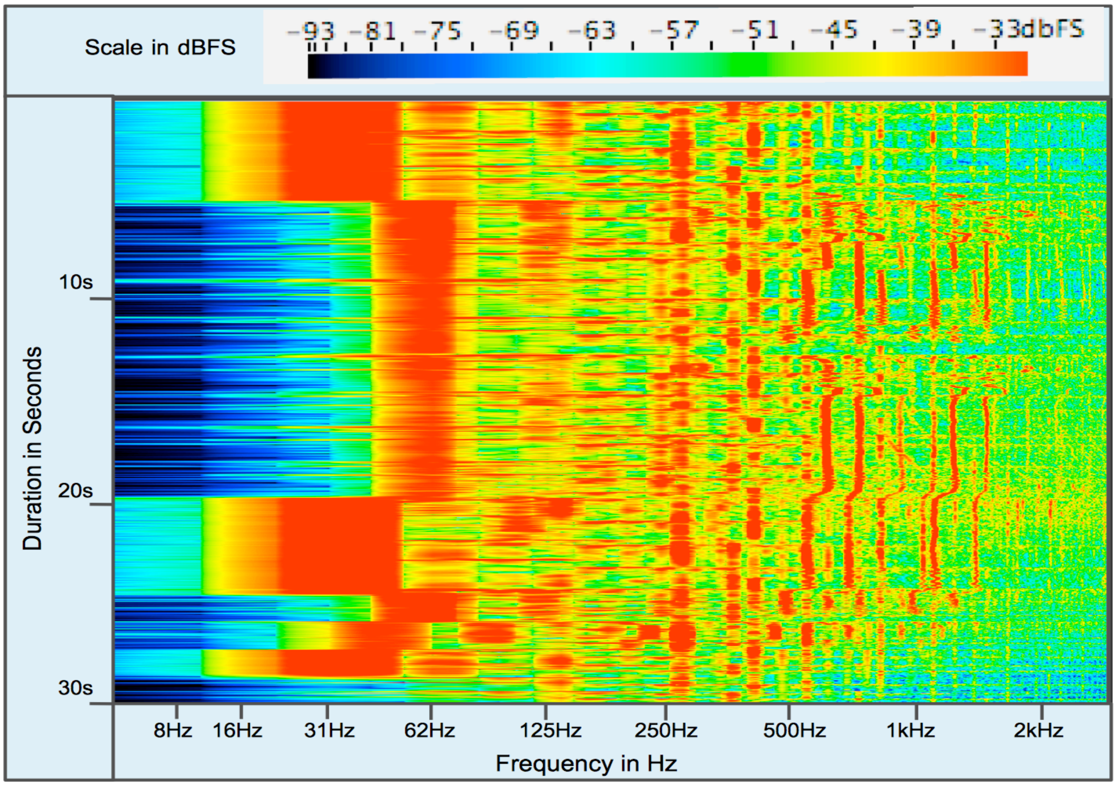

Figure 15: Spectrogram of Newton Faulkner 'Teardrop' (Pop).The thick red vertical banding is produced by a sustained synthesised bass line. Energy can clearly be seen produced by the bass line at 20 seconds below 20Hz. Percussive spikes can also be seen at 9s,13s & 17s. (Spectrogram produced using Spectrafoo with 30 second sample time, frequency scaled from 4 – 2500Hz, 1024 Pt Hanning Window at 44.1kHz giving frequency resolution 43Hz.

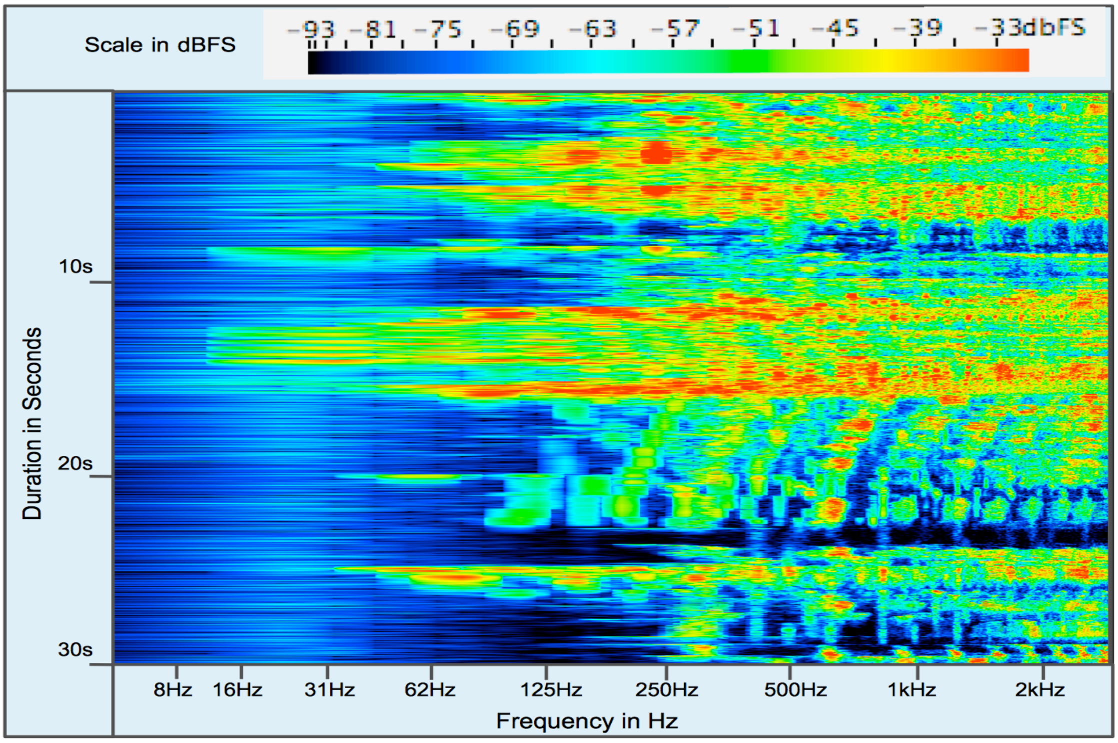

Figure 16: Spectrogram of Elgar 'Dream of Gerontius' (Orchestral). Lacking the low frequency bias of the other genres the percussion can still be clearly seen in the lower frequencies. A crescendo timpani roll can be seen at 13s. (Spectrogram produced using Spectrafoo with 30 second sample time, frequency scaled from 4 – 2500Hz, 1024 Pt Hanning Window at 44.1kHz giving frequency resolution 43Hz.

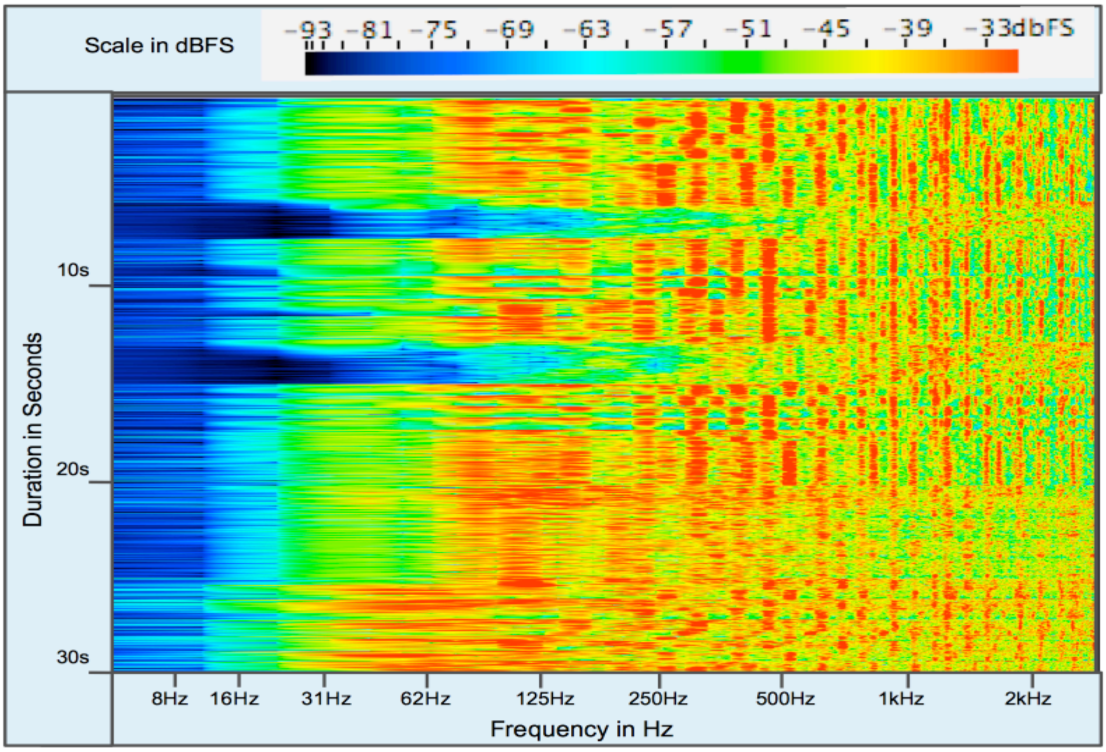

Figure 17: Spectrogram of Tchaikovsky - '1812 - Last Movement' (Orchestral). The timpani and double bass are represented by the higher low frequencies. It is the cannon fired in the finale which are heard and seen in the lower registers at 26s until the end. (Spectrogram produced using Spectrafoo with 30 second sample time, frequency scaled from 4 – 2500Hz, 1024 Pt Hanning Window at 44.1kHz giving frequency resolution 43Hz.

2.3.2. Vibration

Vibration plays a significant role in the perception of music as noted by Merchel and Ercan Altinsoy [51];

"The coupled perception of sound and vibration is a well-known phenomenon during live pop and organ concerts. However even during a symphonic concert in a concert hall, sound can excite perceivable vibrations on the surface of the body".

They also concluded that the listener may not recognise the vibrations as a separate feature because the "*tactile percept is integrated with the other senses into one multimodal percept*".

Work by Harman Audio engineers into automotive sound systems has also looked at the issue of 'whole body vibration' [52]. Their work concluded that the "*presence of whole-body vibration*" could "*reduce the preferred level of bass equalisation by as much as 3dB*". The frequency range looked at in these studies also includes the range often referred to as Infrasound as defined by IEC Standard 801-21-03 [53] . This dissertation will refer to the frequency range being primarily studied as infra-sub (see glossary) as it extends from aurally perceived bass to the range of infra-sound, below the commonly accepted threshold of hearing of 20Hz.

2.4 Human Hearing Systems

The frequency range of human hearing is generally quoted as being between 20Hz and 20kHz [54]. The lowest frequency perceivable by the human ear is generally referred to as between 18Hz and 20Hz, dependent on SPL [55].

2.4.1. Infrasound

Frequencies below 20Hz are commonly referred to as 'Infrasound' and are often mistakenly deemed to be inaudible. However the hearing threshold has been measured reliably down to 4Hz for listening in an anechoic chamber [56][57], and down to 1.5Hz for headphone listening [58]. Figure 18 compares figures taken by Leventhall [56] from Watanabe and Moller's data [57] and compared to the standard hearing thresholds as stated in ISO: 226,2003 [59]. The data is also represented in Table 4 where the hearing threshold level, measured in dB is related to frequency. The perception thresholds for Infrasound are not normally exceeded and listeners would be unaware of infrasound, especially in situations where the infrasound is being masked by frequencies from other environmental sounds. It is clear from Table 4 that although the SPL needed to perceive the lower frequencies is high, it is within the range that could be experienced when listening to music at the levels at which modern concerts operate e.g. 100dBA at 40m (see section 2.2.1) and therefore there will be an audible perception of infrasound below 20Hz. As Leventhall clearly states,

"*The common assumption that 'infrasound' is inaudible is incorrect*" [53].

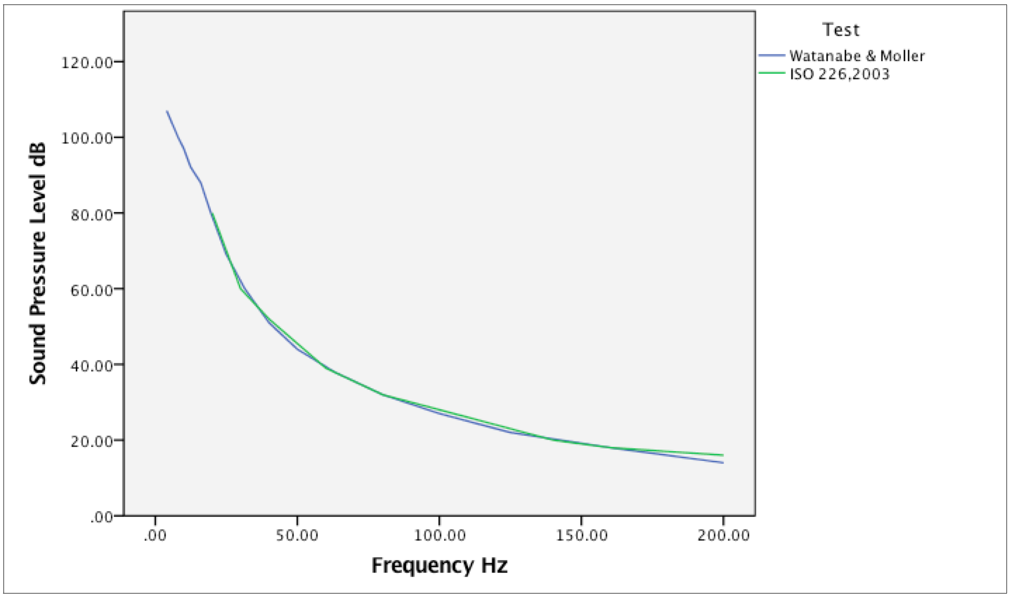

Figure 18: Comparison between the ISO Standard 226,2003 and figures produced by Watanabe & Moller of hearing thresholds at low frequencies. The figures from Watanabe and Moller's research clearly extended below 10Hz [56].

Freq (Hz)	4	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200
dB SPL	107	100	97	92	88	79	69	60	51	44	38	32	27	22	18	14

Table 4: Hearing threshold of bass frequencies in Hz measured at third octave intervals in dB SPL [57].

2.4.2. Mechanosensation

Hearing is the ability, by the detection of vibrations, primarily within the ear to perceive sound. Vibrations are also perceived by the body's 'somatosensory' system. The somatosensory system consists of four main types of receptor: Nocireceptors (pain), proprioceptors (body position), thermal receptors (cold and warmth) and mechanoreceptors (e.g. Vibration, pressure, stretching). There are four different mechanoreceptor types in glabrous (hairless) skin: Merkel's Receptors, Ruffini's corpuscles, Meissner's corpuscles and Pacinian corpuscles as seen in Figure 19 [60].

Music induced vibration of the skin primarily excites the Meissner and Pacinian corpuscles. The Meissner corpuscles are most sensitive to vibration below 40Hz, at higher frequencies the Meissner corpuscles threshold rises and the Pacinian corpuscles dominate perception [61].

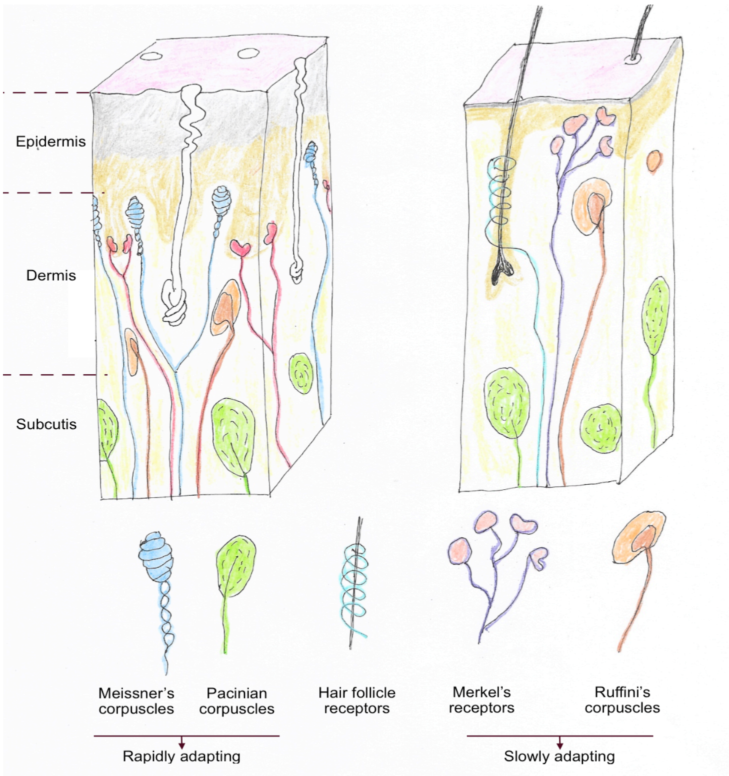

Figure 19: Illustration of the mechanoreceptors in the hair and hairless skin of primates. Merkel's receptors and Meissner's corpuscles can be found close to the surface. Pacinian corpuscles and Ruffini's corpuscles lie deeper in the tissue (adapted from Merchel & Altinsoy [60]).

Vibration detection in the skin by these mechanoreceptors [62], bone conduction and body resonances (such as in the chest cavity) [63] all contribute to the perception of airborne low frequency noise. Mechanosensation is particularly noticeable in the 50Hz to 100Hz range where chest resonance occurs [64]. It has been speculated by Takahashi and Maeda [65] that this is due to opposite movements in the abdomen and back caused by isotopic pressure changes. They concluded that the human body acts "*As a mechanically linear system in response to airborne vibrations generated by complex low-frequency noise"* [65].

An investigation into sound and vibration perception of both hearing and profoundly deaf people showed an ability to perceive noise through the surface of the subjects body, both deaf and hearing, if the SPL was in excess of normal hearing thresholds. The research by Yamada, Ikuji, Fujikata and Watanabe [66] indicates that the perception of sound is not confined to the ear mechanisms or auditory systems. Moller and Pederson [67] summarise that "*hearing becomes gradually less sensitive for decreasing frequency, but there is no specific frequency at which the hearing stops*". They saw reasonable agreement between studies of hearing thresholds, represented down to 20Hz by ISO but they also proposed a *"normal threshold one decade further down in frequency*" to 10Hz.

Leventhall [68] noted that the majority of studies into low frequency noise use a spring mass model for mechanical vibration into the feet or seat. A spring mass model is a simple harmonic motion with an assumption that the amount of stretch is proportional to the restoring force, and that the mass glides easily without loss of energy. As Leventhall states in his work on "Somatic Responses to Low Frequency Noise" the spring mass model is not suitable for body vibration generated by low frequency airborne vibration as it is a compressive effect on the whole body and consequently a more complex scenario. In their study of music induced vibrations Merchel and Altinsoy [69] concluded that mechanosensation effects of low frequency content at music concerts, which can be felt through the feet or seated area, are predominantly airborne vibrations . In open air festivals there are limited non-airborne vibrations as the audience is standing, the ground is solid, and is in all practical terms non-resonant at the sound pressure level experienced by the audience. Where audiences are standing non-airborne vibration is limited to that through the feet, so whole body vibration (WBV) is predominantly airborne.
Physical responses to sound are an integral part of the listening process. The link between WBV and aural perception has been well established and is detailed well by Walker, Sungyoung, and Martens [70]. The research described here will be concentrating on the effects of airborne WBV.

2.4.3. Missing Frequencies

The low frequency content of music, such as that often produced by percussion and some bass and keyboard instruments, is capable of producing mechanosensation. Music in a concert hall when heard without sound reinforcement contains the Infra-sub content, shown by Merchel and Altinsoy [71] to add to the overall listening experience . However when a concert is amplified there is limiting of the frequency range by the public address speaker system. Line array systems typically have a frequency response of between 50Hz and 18kHz as shown in the example of D&B Audiotechniks 'J series', and detailed in their specifications online [72]. With the addition of subwoofer cabinets the system frequency range can be extended down to 32Hz (figures again based on the popular "J- Series" by "D&B Audiotechnik and detailed in their online manual [73]). In response to an increased interest in frequencies below 40Hz D&B Audiotechnik released a cabinet designated the "J-Infra" Subwoofer. It is one of the few production speaker cabinets which can reproduce frequencies below 28Hz (Figure 20) as detailed in it's online manual [74].

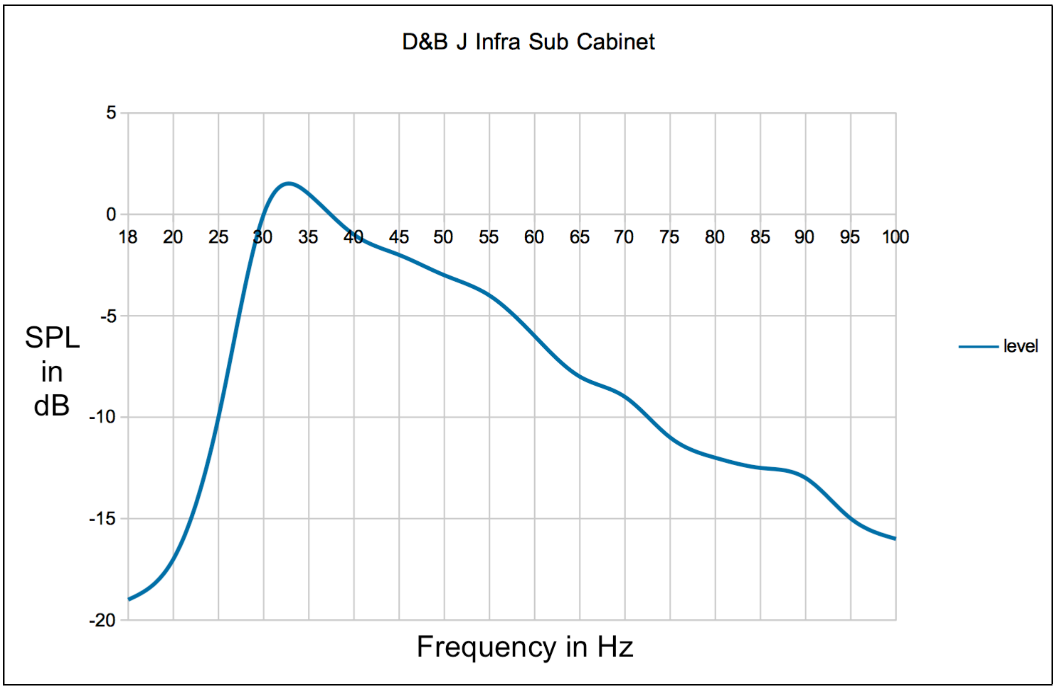

Figure 20: Magnitude response plot of D&B J-Infra Subwoofer cabinet showing its low frequency extension below 30Hz (+/-3dB).

2.4.4. Loudness Compensation

The first experimental data published by Fletcher and Munson in 1933 [75] established that there is considerable difference between the ear's response at different SPL, most noticeably at the extremes of the hearing frequency range. This led to the development of loudness curves (introduced in section 2.2.2). Equal Loudness contours, as they are now known, are a measure of sound pressure level over the human hearing spectrum, where the listener perceives a constant loudness (psycho-physiological correlate of physical strength, or amplitude, of a sound). The contour changes relative to sound pressure levels. The current equal loudness curves are specified and defined in ISO 226:2003 [76] and shown in Figure 21.

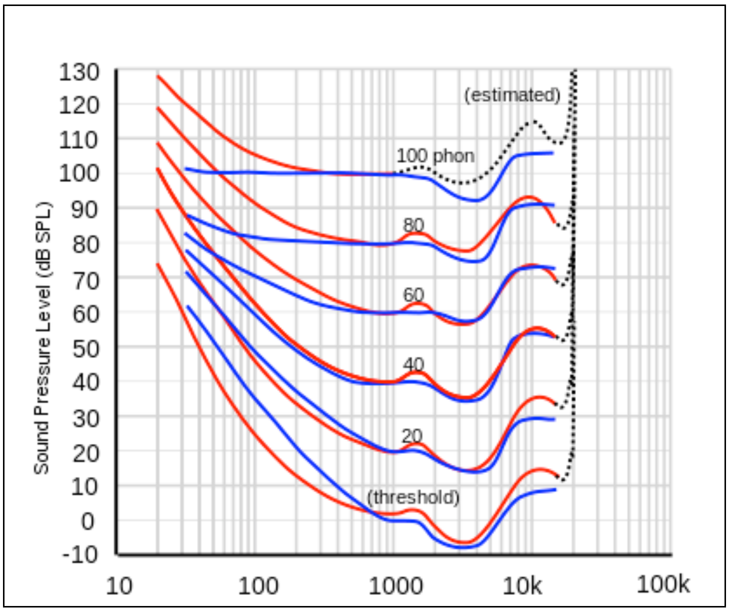

Figure 21: ISO Equal loudness curves (red) (from ISO 226:2003 revision) and Fletcher-Munson curves (blue) for comparison.The ISO curves represent the latest accepted data and are seen as an improvement and progression of Fletcher and Munson's original work as represented by the blue curve.

2.4.5. The Loudness Control

Loudness curve derived equalisation controls were developed by HiFi manufacturers to compensate for listening perception at different SPL. Although they became popular features of Hi-Fi amplifiers in the 1970s and 1980s they have fallen out of popularity and are less prevalent now. Holman and Kampman [77] found that although they could be effective, the compensation curves would often be over accentuated. Figure 22 shows the effect of a Loudness Compensation Control [78]. The A and C weighting curves marked in the illustration are mirrored by the equalisation circuit. When activated the equalisation circuit can be varied from an inverse of the C-weighted curve (c-weighted: purple line, inverse-purple dotted line) gradually to a shape that mimics an inverse of the A-weighted curve (a-weighted: red line, inverse: dotted red line). The equalisation control helps compensate for the perceived lack in level at different frequencies, dependent on SPL.

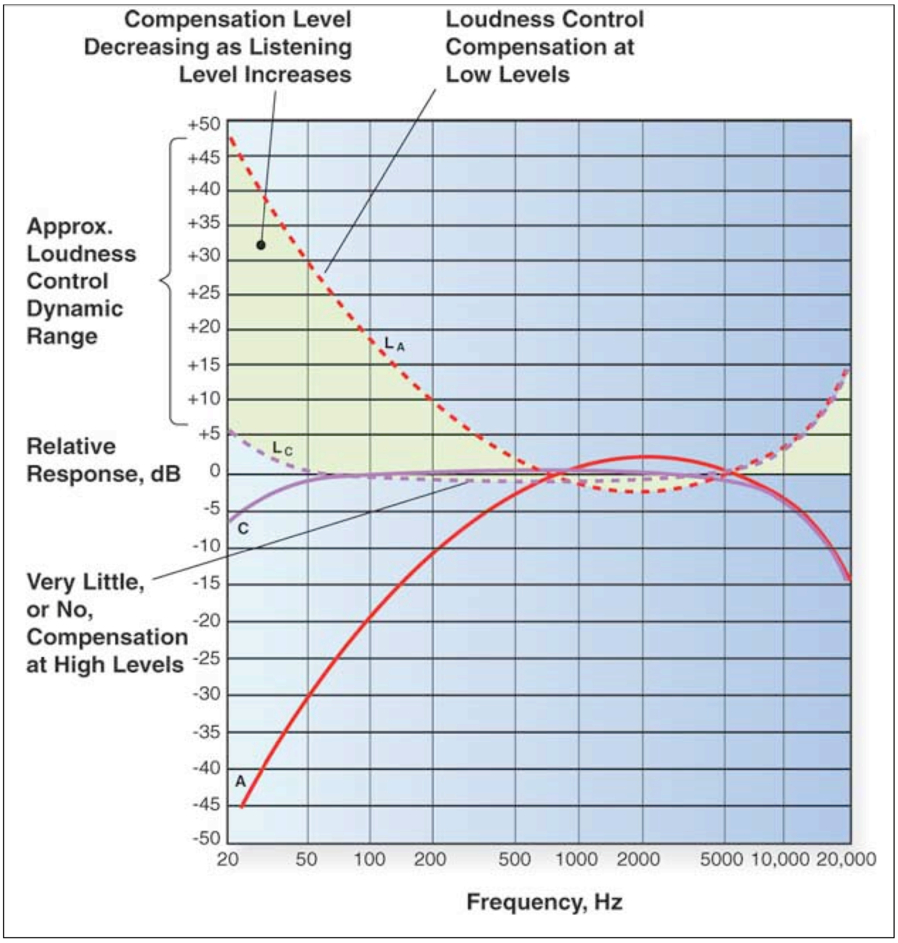

Figure 22: Graph showing the A (Red bold line) & C (purple bold line) Weighted loudness curves and the effect of loudness compensation equalisation (corresponding dotted lines). The green shaded areas indicate the increased/decreased area of level change [78].

2.4.6. Just Noticeable Difference

Humans ability to perceive small differences in sound is quantified using the concept of the 'Just Noticeable Difference' (JND). The JND is the amount a stimuli must be changed in order for a difference to be noticeable, in a test. This is usually set as being detectable at least 50% of the time. The JND is also referred to as DL or Difference Limen. Measured in physical units:

$$\frac{\Delta I}{I} = K_w \qquad (1)$$

Where I is the original intensity of the particular stimulation, ΔI is the addition to it required for the change to be perceived (the JND), and K_w represents Weber's constant (which does not change in relation to I) [79].

Equation 1 is based on Weber's Law, which states that the Difference Limen in intensity ΔI is a constant, and that the JND increment is a fixed percentage independent of whatever level was used as a starting point [80]. This law is only broadly true but has formed the basis for many studies. The work of Houtsma, Durlach and Braida [81] using white noise and a 1KHz sine wave indicates that a JND of 0.54dB SPL would be an appropriate reference for a JND at SPLs of between 80dB and 90dB SPL.

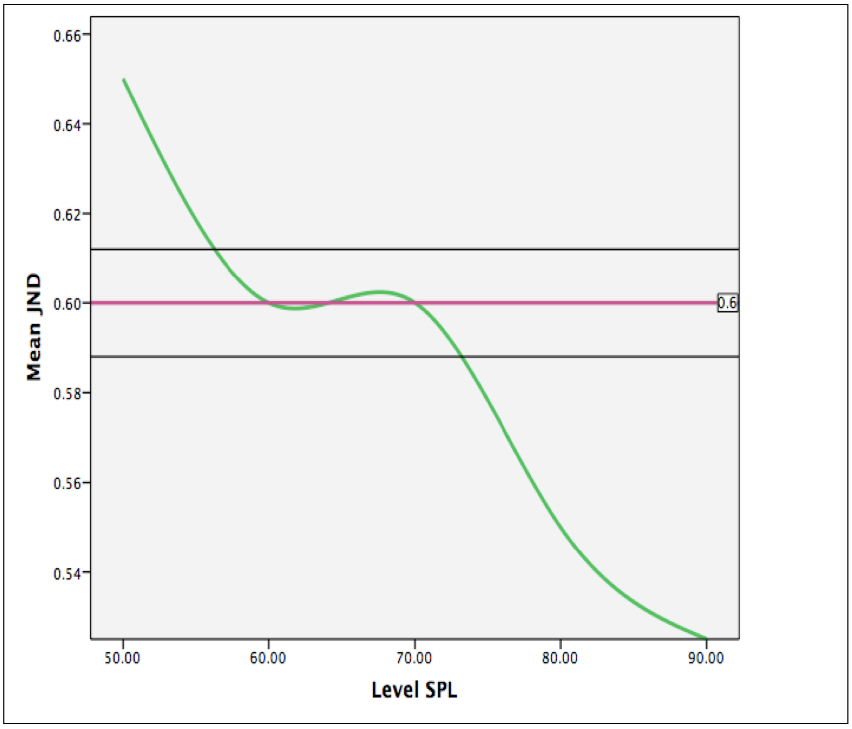

Figure 23: Graph showing the relationship between the mean Just Noticeable Difference (JND) and Sound Pressure Level (dB SPL). A choice of 0.54dB SPL was made as this level encompassed the lowest SPL found in testing and was greater than at higher SPLs [81].

3 Research Agenda

With the increasing amount of noise restrictions being imposed on musical concerts, both indoors, and out-doors, it has become important to find ways of maintaining a positive audience sonic experience at lower SPL. Part of improving this experience may involve the physicality of sound, the way the body perceives sound not just aurally but with other forms of mechanosensation not associated with the ear, which help produce a more involving and positive concert going experience.

The present research aims to investigate whether the use of techniques adapted from the HiFi Loudness Equalisation Control, the manipulation of SPL's at low frequencies, combined with an extension of the low frequency range of the sound system (to encompass the < 50Hz region) to promote WBV, provide audiences with a preferred listening level at lower SPL.

3.1 Hypothesis

Hypothesis: the preferred listening level of amplified music will be significantly lower when the low frequency content (Infra-sub) of the presented audio material is increased. ‘Increased Infra-sub content’ refers to an increase in sound pressure level in the region below 50hz, together with an extension of frequency range down to 18Hz.

If this hypothesis is supported, meaning that increased Infra-Sub content does indeed significantly lower the overall preferred listening level, it will indicate that including increased Infra-sub could be implemented in situations where a lower overall dBA SPL, whilst maintaining the audiences satisfactory listening experience, is required.

3.2 Listening Tests

A listening test was designed to test the hypothesis. The test was designed to compare the preferred listening levels (PLL's) of three genres of music under two differing conditions. The first condition, NORMAL, utilising a standard large format line array speaker system. The second condition, INFRA, utilising the same large format line array speaker system but with the addition of increased Infra-sub content.

3.3 Method

Participants were asked to listen listen to three music tracks, one from each musical genre, Pop, Dance and Rock. Each track was listened to twice, once under the condition NORMAL and once under the condition INFRA. The tracks were presented in a random order with no indication as to under which condition the tracks were being played. On each occasion the participant was asked to start with the volume on silent, and using the controller, increase the level to one they preferred, appropriate for a speaker system of this size. The controller level was then reset to silent and the next track played. Measurements were taken of the SPL of the participants PLL at the listening position.

3.4 Test Design

3.4.1. Music

Music was chosen that was popular, and therefore of significant importance culturally. Tracks were chosen that would be instantly recognisable as stylistically representative of each three genre. Although it is impossible to capture a genre in a single track it was felt each track would be recognisably of its type. The music genres chosen, Rock, Pop and Dance, also represent those most often heard at amplified music festivals [1]. One track was chosen in each genre.

The tracks chosen were :

Rock : Rage Against the Machine: “Killing in the name of.” [82]

Dance : Chemical Brothers: “Go” [83]

Pop : Katey Perry: “Fireworks” [84]

60 second segments from the middle of the each track were utilised. The tracks chosen have a sufficient frequency range in their spectral content to ensure that there was significant audio

information below 50Hz as illustrated in Figure 24. The tracks were analysed using a fast Fourier transform (FFT) in Spectrafoo using a Hanning window of 1024 sample points at a sample rate of 44.1kHz . The samples were taken over a 30 second period toward the middle section of the track and the results averaged over that period. The dance and pop tracks have very similar profiles below 80Hz, the rock track dips gradually from 50Hz but has the same level at 40Hz and 25Hz.

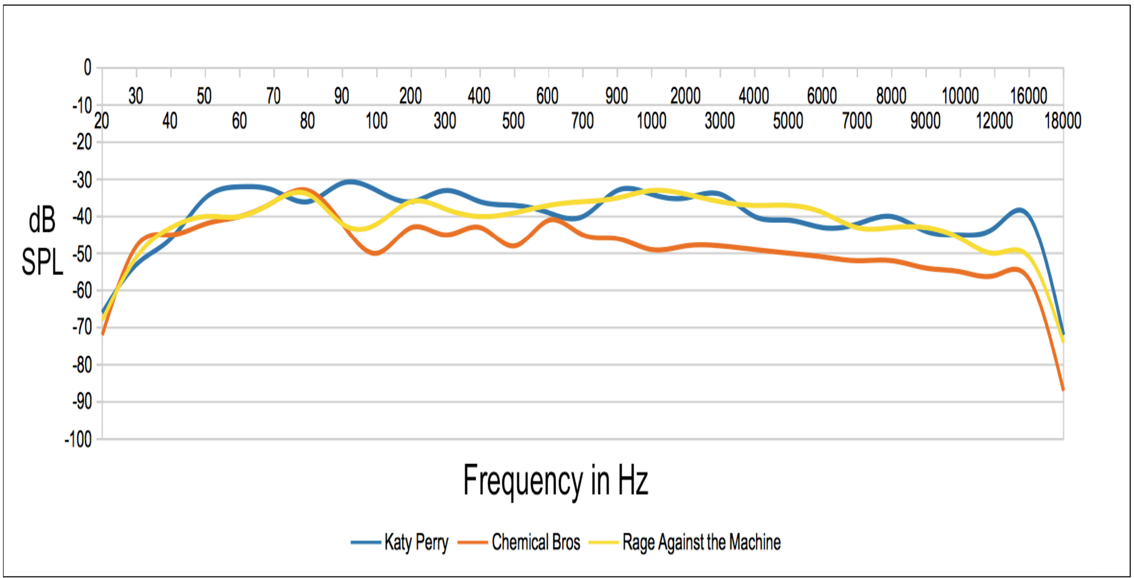

Figure 24: Magnitude response plots of the three chosen tracks. Data was taken over a 30 second period and levels averaged to produce a mean averaged level. The level is measured in dBFS. As cab be seen all tracks have significant dB SPL below 50Hz.(Blue-Pop, Red-Dance, Yellow-Rock).

The dance track has a lower SPL than the other two genres over the frequency range 30 -12000Hz but is comparable in the low frequency region 30 – 80Hz where the SPL difference is < +/- 1 dB, as seen in Table 5.

Genre	Mean SPL 30-12000Hz	Mean SPL 30-80Hz
Pop	-38.2	-39.2
Dance	-46.6	-40.7

Table 5: Table showing the mean SPL of the three chosen tracks. The first mean column is the average over 30 seconds over the frequency range 30-12000Hz, the second column is the frequency range 30- 80Hz.

3.4.2. Test Sites

The test criteria required a large controlled space so that the effects of room acoustics were minimised (see section 4.4), as well as being able to accommodate a speaker system capable of stimulating mechanosensation <30Hz. The tests were carried out during The Prodigy "The Day is my Enemy Tour" [85] . The test venues were all >10,000 capacity indoor arenas;

- Birmingham National Indoor Arena, Birmingham, UK.
- Wembley Arena, London, UK.
- Siemens Arena, Vilnius, Lithuania.

The test were made in a 'real world' setting using a currently touring large format line array speaker system (detailed in section 4.2.3.) The venues were all sufficiently large that the Schroeder frequency [86] was below the frequency range being studied (<8Hz for all venues). Room resonances are characterised by a crossover frequency, the 'Schroeder frequency', that marks the transition from individual, well-separated resonances to many overlapping normal modes. Below the crossover frequency the resonances have the potential to significantly degrade any original musical signals [87].

The listening position was at the 'Front of house' mix position in each venue. The FOH position where the sound engineer listens to, and mixes, the show, in this situation 32m from the downstage edge. Every aspect of the touring sound system was transported between venues so there was good continuity for comparison. Venues were chosen based on venue size, type and time considerations. The majority of the testing was done at Wembley Arena over a two day period.

Birmingham Barclaycard Arena, UK

5 tests were carried out at Birmingham Barclaycard Arena (Figure 25). This is a large indoor arena with a capacity of 15,800 for a standing show. A multipurpose venue, its ability to host music concerts was enhanced with a refurbishment in 2014 [88]. Although like many indoor arenas there are large reflective areas, listening tests concluded that these had no perceived affect on the sound at the test listening position.

Wembley Arena, UK

22 tests were carried out at Wembley Arena (Figure 26). Having been originally constructed as a swimming pool for the 1934 Empire games [89] and previously having a reputation for poor acoustics, these were greatly improved with a refit in 2006, with acoustic treatment being added. The venue has a capacity of 12,740 for a standing show.

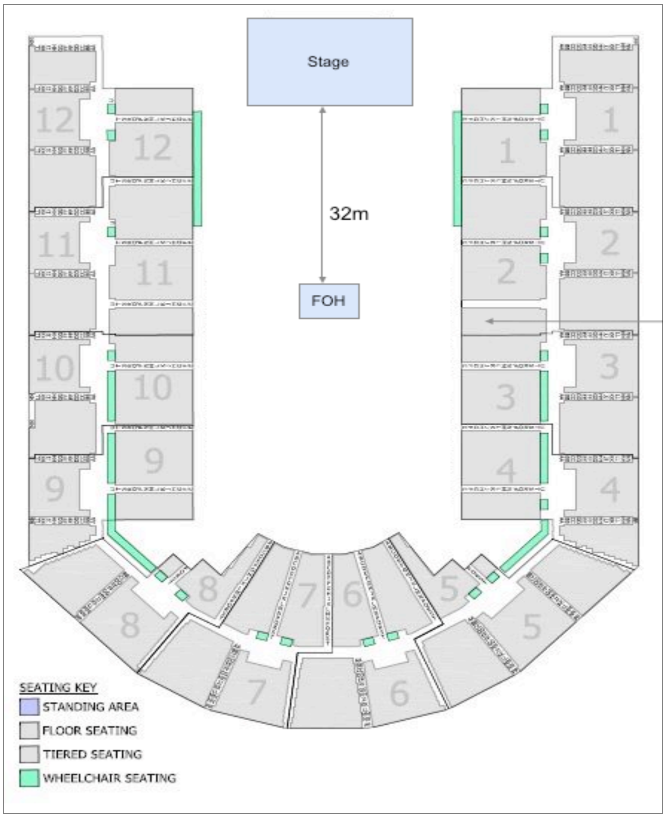

Figure 25: Diagram of Birmingham Arena showing seated areas, FOH Mix and stage positions (Not to Scale).

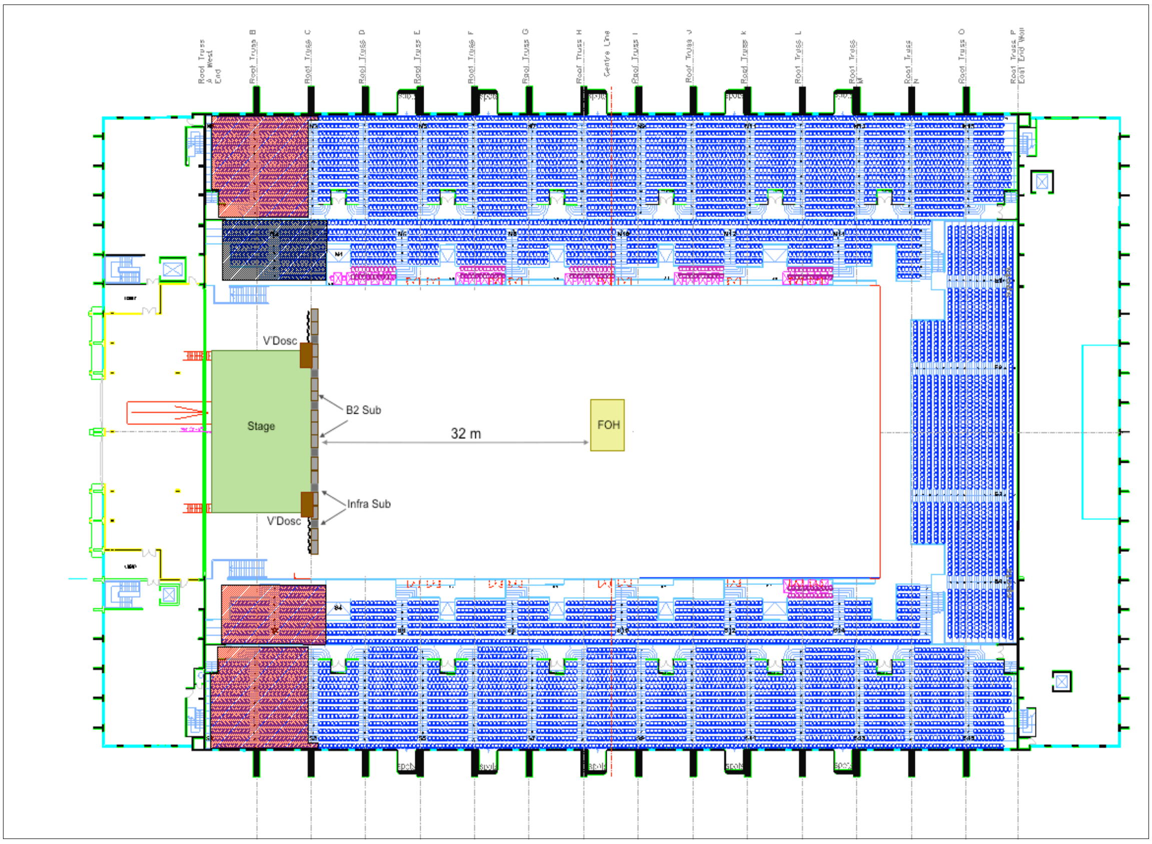

Figure 26: Diagram of Wembley Arena showing seating, position of stage an FOH. Speaker array positions are also shown (Not to Scale). Seating is shown in blue (pink shaded indicates seating not used).

Siemens Arena Vilnius, LT

Eleven tests were carried out at Siemens Arena, Vilnius, Lithuania (Figure 27), a modern 12,500 capacity multipurpose arena. Opened in 2004 it was built to house large entertainment events, business and sporting events [90].

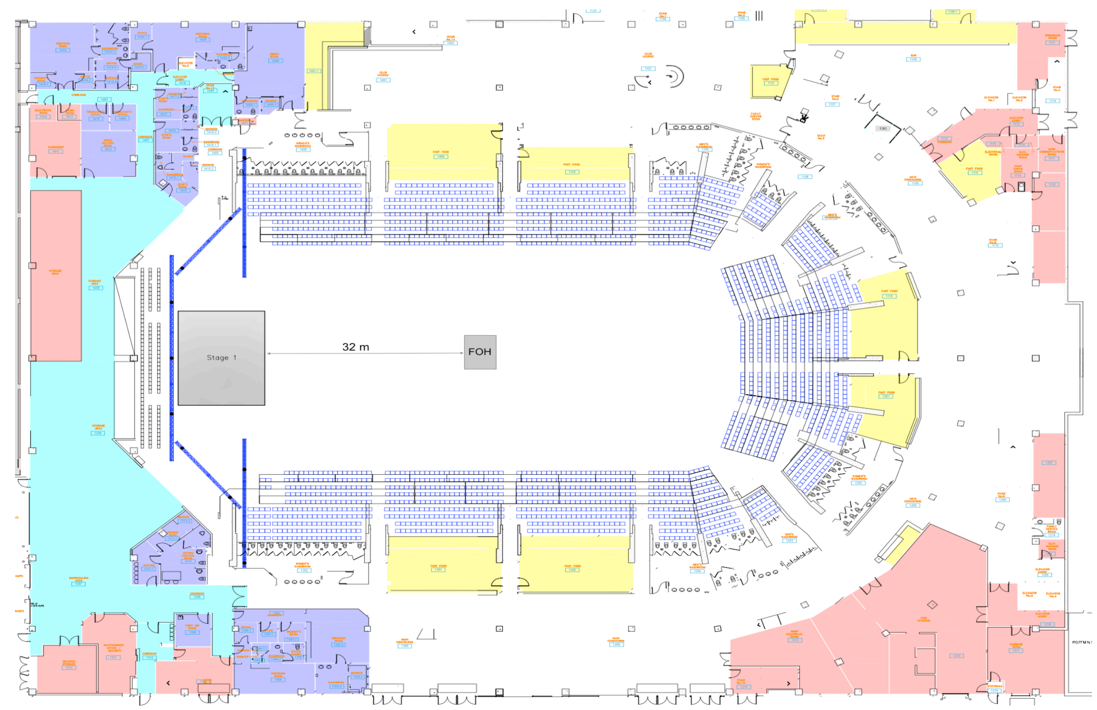

Figure 27: Diagram of Vilnius Arena showing Stage and FOH positions. (Not to Scale). Seating is shown in blue.

3.4.3. Speaker System

In order to ensure the ecological validity of the test it was conducted utilising professional tools and practices standard in the live sound reinforcement industry wherever possible. The test sites were concert venues and all the equipment was set up for concert performance. The speaker system used was a large format line array system (L'Acoustics V'Dosc [19]) with low frequency extension (D&B Audiotechnik B2 [91] & Infra Subwoofer speaker cabinets [72]). The speaker system chosen represents a typical system type (line array) for the majority of arena concert shows of this kind worldwide and the manufacturers are established market leaders [92].

Figure 28: Main Speaker system used in the listening test showing the L'Acoustics V'Dosc Line array (A), D&B AudioTechnik B2 (B) and D&B AudioTechnik J-Infra subwoofer speakers (C).

The system consisted of a left and right symmetrical speaker hang, each comprising of 16 'V'Dosc' cabinets as seen in Figure 28, marked 'A'. The 'V'Dosc' system covered the frequency range from 60Hz to 18KHz [93]. The system was equalised using a Meyer Sound Galileo Callisto Array Processor [94] using Meyer Sound Compass software [95]. The line array equalisation consisted of a 2dB reduction at 130Hz and a high pass filter introduced at 65Hz, as seen in Figure 29. Further equalisation was applied to the D&B B2 subwoofer cabinets in the form of a low pass filter applied at 90Hz (Figure 30). The D7B Infra subwoofer cabinets had a low pass filter applied at 54Hz as well as a boost applied at 35Hz (Figure 31).

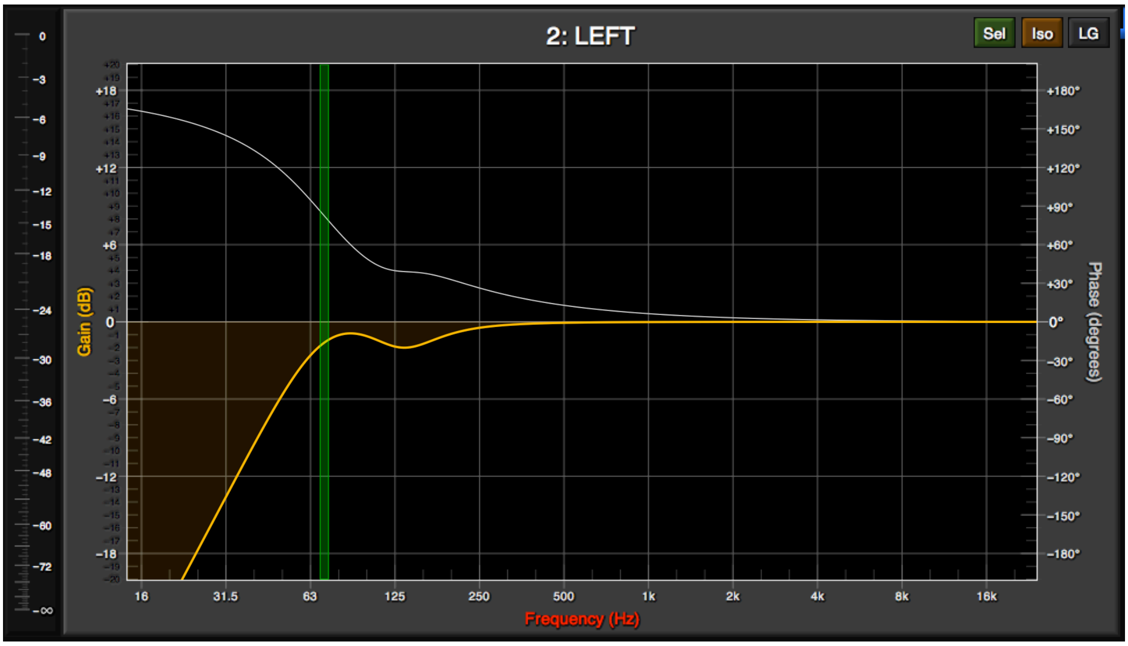

Figure 29: Callisto equalisation plot of the V'Dosc speaker system showing gain (yellow line) and predicted phase changes (white line) with the high pass filter (green line) applied. Screenshot of Meyer Sound Compass Software.

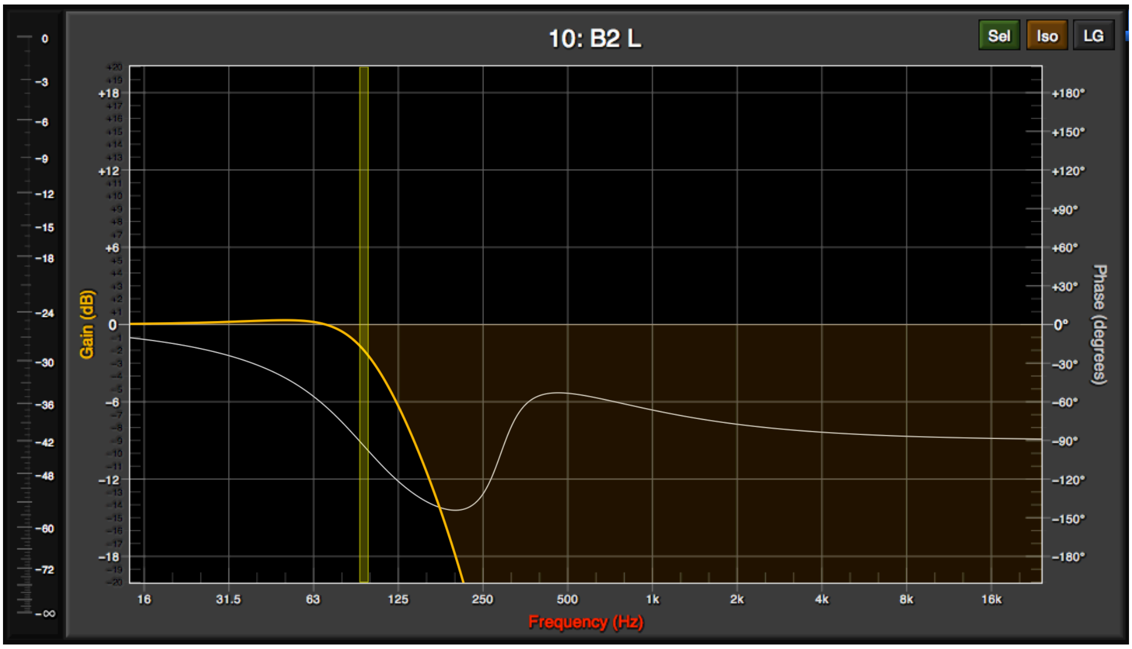

Figure 30: Callisto equalisation plot of the D&B B2 Subwoofer showing gain (yellow line) and predicted phase changes (white line) Green line indicates low-pass filter cut off frequency. Screenshot of Meyer Sound Compass Software.

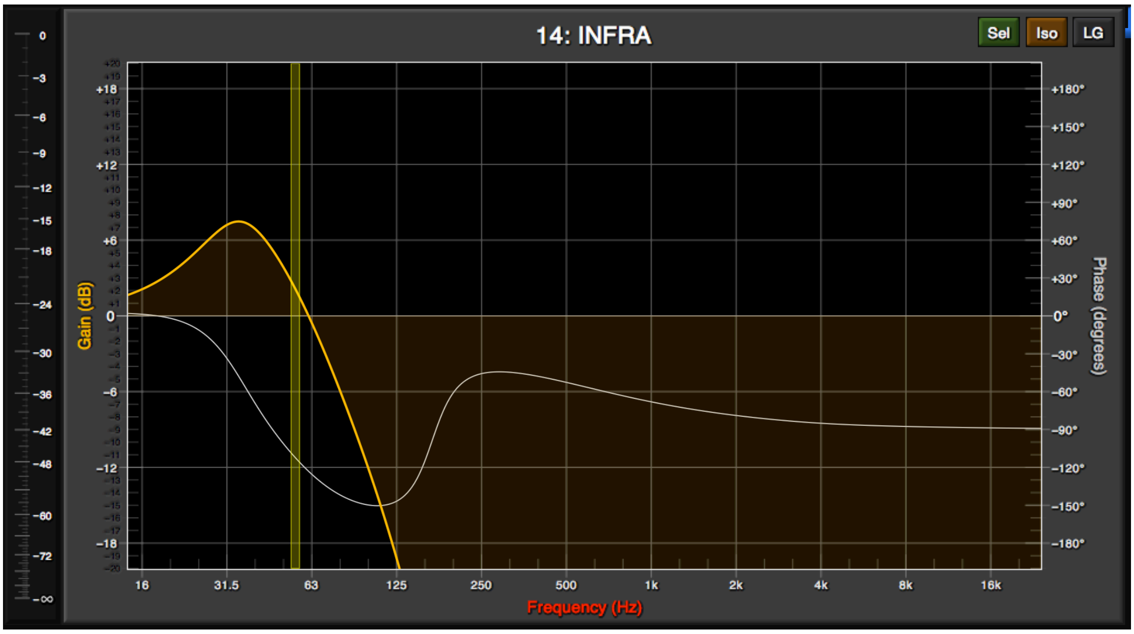

Figure 31: Callisto equalisation plot D&B J-Infra Subwoofer equalisation showing gain (yellow line) and predicted phase changes (white line) . The green line indicates low-pass filter cut off frequency (54 Hz). Screenshot of Meyer Sound Compass Software.

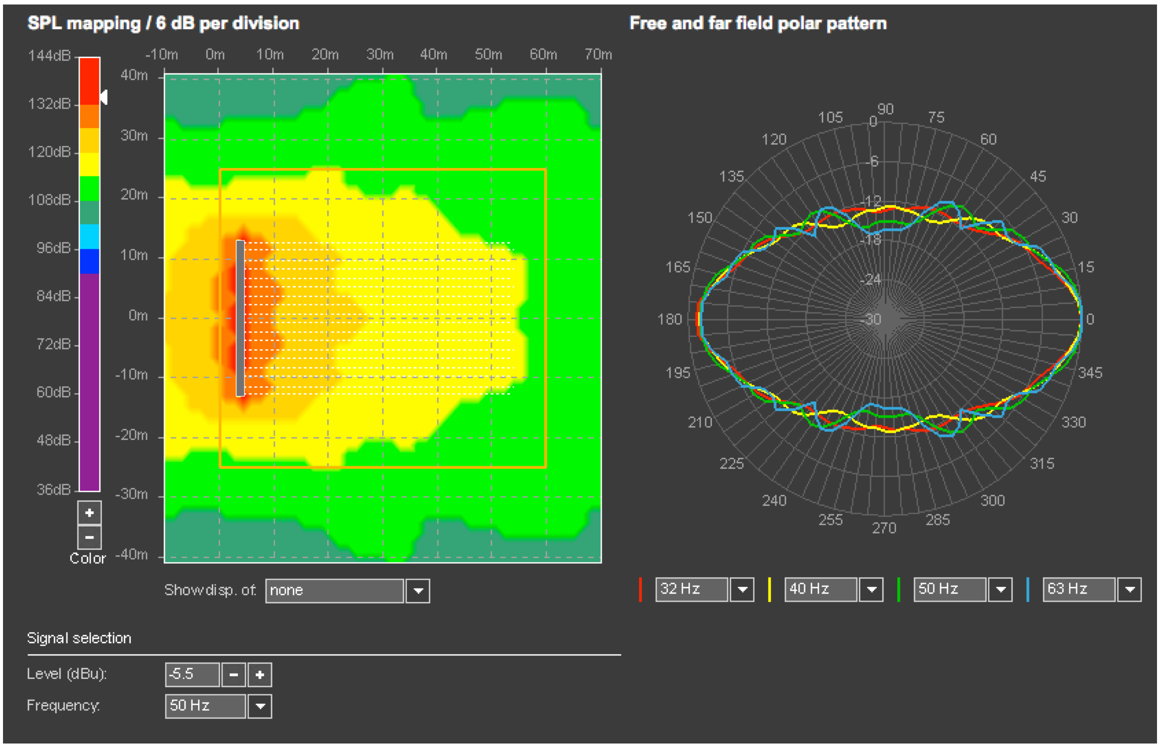

Figure 32: SPL prediction of D&B B2 subwoofer cabinets in Wembley Arena. The yellow box represents audience area. The Subwoofer cabinets are marked as a grey solid line on the plot. The B2 cabinet is not cardioid in design, the figure on the right demonstrates the almost omnidirectional output. The plot is based on the centre of the array. (Prediction based on an array of 28 D&B B2 Sub Cabinets at a listening height 1.7m, resolution 1m, air absorption 24◦C/60% Humidity, @ 50Hz).

The SPL produced by the B2 and J-Infra sub cabinets coverage was optimised using D&B 'Array Calc' software [96]. The 'Array Calc' software calculated the delay values to create a virtual arc (see section 2.1.7.) to achieve an even coverage (Figure 32). The subwoofer speaker cabinets were stacked in a crenellated broadband array as seen in Figure 28. The SPL coverage throughout the venue was within +/- 6dB for the primary audience area covered by Line Array/Subwoofers [Figure 32]. Coverage was checked using a calibrated hand held decibel meter. The SPL readings measured with the hand held meter correlated well to the D&B Arraycalc predictions for the system (+/- 2dB between the actual and predicted levels – see Table 16 : Addendum Data, page 74). Due to limitations in the proprietary software it was not possible to produce a combined prediction of the D&B B2 Subwoofers with the D&B Infra-subwoofers.

Amplification was provided by LabGruppen (V'Dosc) [97] and D&B D80 (Subwoofers) [98] amplifiers. The system was networked using proprietary controllers all fed via the Meyer Callisto Digital Array Processor. All signals once entering the Callisto remained in the digital domain distributed via an Optocore digital network [99] to the amplifiers.

System measurement checks were made using a 'Smaart' PC based measurement system [100]. Measurement readings were taken at different points in the venue and all loudspeakers phase and time aligned to a central point at the centre of the stage, 6m from the downstage edge, using a pink noise test signal. The frequency plots can be seen in Figures 33 and 34.
Music tracks prepared for the listening tests were played from an Apple MacBook Pro via a UAD Apollo Twin interface [101], which also provided level control. Music tracks designated NORMAL were played through the V'Dosc Array and D&B B2 Subwoofer cabinets. Music tracks designated INFRA were played through the V'Dosc Array, D&B B2 Subwoofer cabinets in addition to the D&B J-Infra subwoofer cabinets.

3.4.4. Low Frequency Extension

A comparison between the NORMAL (V'Dosc Array and D&B B2 Subwoofer cabinets) and INFRA (V'Dosc Array, D&B B2 Subwoofer cabinets and D&B J-Infra subwoofer cabinets) array, shown in Figures 33 and 34, clearly shows the low frequency extension beyond the NORMAL system low frequency response, provided by the addition of the D&B J-Infra subwoofer cabinets. The addition of the J-Infra subwoofer cabinets lower the frequency range from a frequency drop-off point, where the SPL declines steeply (ie: greater than -6dB) from the stated loudspeakers frequency range, from 38Hz to 18Hz, representing an octave of extension. Although musical tones at these frequencies have low pitch salience [102] they form an important component of many musical sounds, particularly percussive sounds, contributing not just to the tonal but rhythmic quality of music [103].

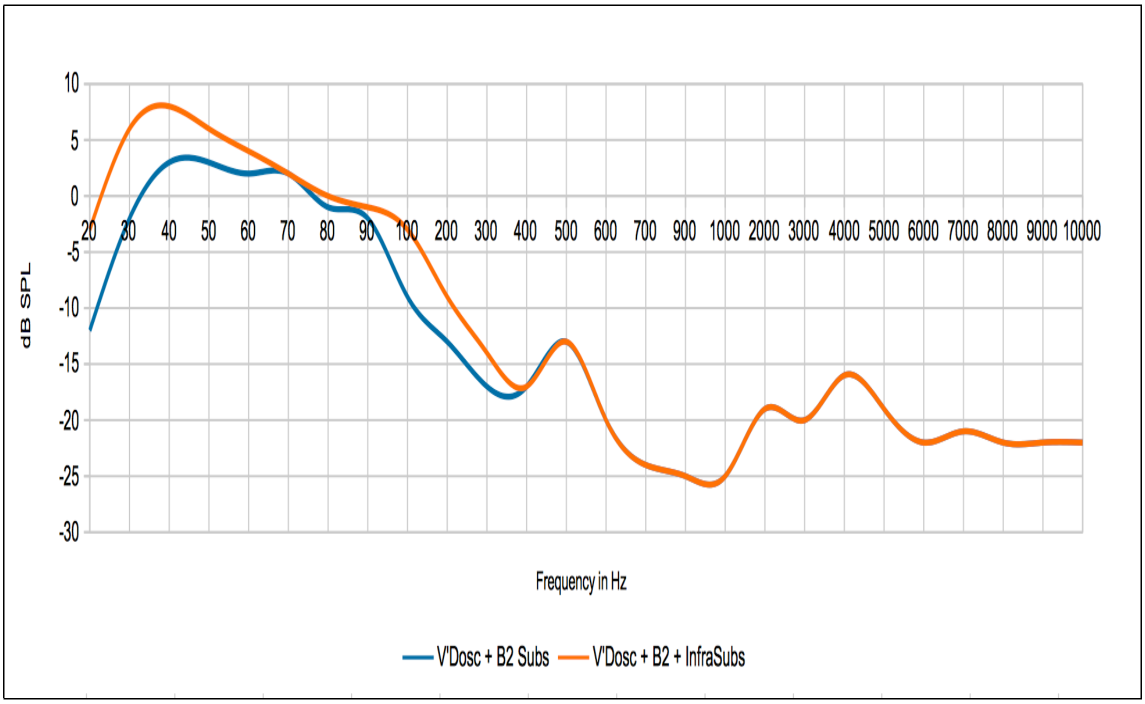

Figure 33: Magnitude response plots for comparison of Normal Array (V'Dosc Line Array + D&B B2) (Blue Line) and Infra Array (V'Dosc Line Array + D&B B2 Array+ D&B J-Infra Subwoofer)(Orange Line) . Measurements were taken with Smaart measurement software using averaged traces of pink noise at 90dB SPL at the FOH Mix position.

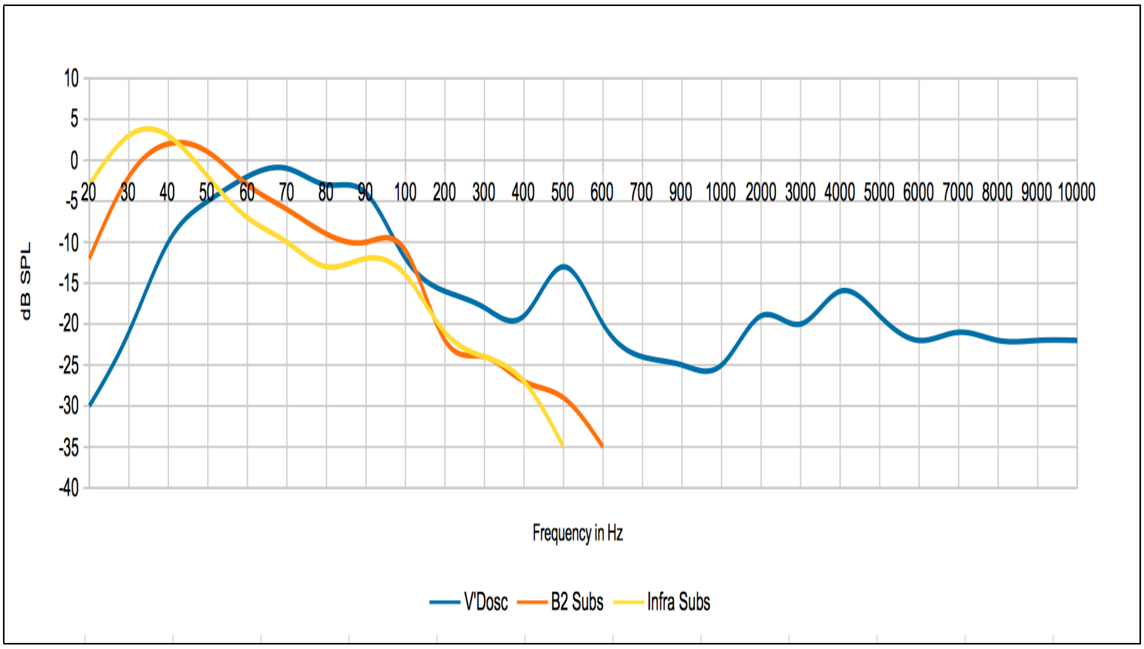

Figure 34: Magnitude response plots for comparison of V'Dosc Line Array (Blue Line), D&B B2 Sub Array (Orange Line), D&B J-Infra Subwoofer Array (Yellow Line). Measurements were taken with Smaart measurement software using averaged traces of pink noise at 90dB SPL at the FOH Mix position.

The choice of Speaker system was dictated by the touring system which combined speakers from more than one manufacturer. Although this is unusual it is by no means unknown. The L'Acoustics V'Dosc is a very well established and well known large format line array. The D&B Audiotechnik B2 subwoofer is also a well established cabinet. The D&B Audiotechnik J-Infra Subwoofer is a less well known cabinet but one that fills a niche position with its extended cardioid low frequency output. The combined system worked well as a cohesive system and was utilised for over twenty concerts on the tour prior to the tests.

3.4.5. Test Metering Calibration

The controller used for the experiment, a UAD Apollo Twin Audio Interface featured remote software monitoring. The level of the controller was only visible to the tester as a read out on the control laptop [Figure 35], The Apollo controller was calibrated using a clip of pink noise, with the numeric read out referenced to a dBA reading taken using two laptops running '10Eazy' [104] PC based Class 1 noise measurement systems. This produced a calibration scale (Figure 7) by which an SPL reading could be produced based on the read out of the controller remote software monitor (Figure 36). The 10EaZy measurement microphones were placed 2m apart either side of the listening position in order to cover the possible area the subject would stand, whilst leaving it clear of obstructions. An average was taken of the two measurement systems. The level measurements were taken using the A-weighted scale, the weighting most often used in live concert situations (see section 2.2.2).

Figure 35: The test position showing the tandem laptops running the 10EaZy measurement system. Remote control of the sound system was provided by the Callisto remote control software running on an iPad Mini. The UAD Apollo controller used by participants can be seen in the centre of the picture on the mixing console, all markings indicating level were blacked out. The laptop screens were not visible from the listening position .The Apple Macbook is running the test music as well as monitoring the level on the Apollo controller via a remote window.

The equipment used in testing was chosen for its relevance to professional use in the field of sound reinforcement. 'Smaart' [100] and 'Spectrafoo' [105] are standard measurement tools for Large Format Line array set-up and calibration. '10EaZy' [104] is commonly used worldwide for 'on' and 'off-site' measurements of dB SPL at open air concerts and in venues requiring engineers to mix below a prescribed SPL. D&B Audiotechnik's 'Array Calc" is a proprietary software based design tool for D&B loudspeakers. It is used to assist the mechanical design as well as prediction of the SPL and dispersion of speaker array designs.

3.4.6. Sound Pressure Levels

The levels of the two conditions, INFRA and NORMAL were trimmed to measure the same SPL on the A weighting scale.

The system was measured before, and after, each test session using a clip of pink noise. The calibration was set so that when the controller level was set to 5.5 it measured 98dB 1 min Leq across both 10EaZy meters. This correlated with the six test music clips which all averaged the same level on a 1min Leq. A correlation chart (Table 6) was drawn up using pink noise at the levels registering on the controller. The controller was mapped across the SPL range as shown in Table 6.

Figure 36: Apollo Controller remote level window. This was visible to the tester via a window on the Apple Macbook. The level used is seen below the rotary control. Movement of the control could also be seen by the tester.

Controller Level	Pink Noise Level (dBA)
14	89
13.5	90
13	90.5
12.5	91
12	91.5
11.5	92
11	92.5
10.5	93
10	93.5
9.5	94
9	94.5
8.5	95
8	95.5
7.5	96
7	96.5
6.5	97
6	97.5
5.5	**98**
5	98.5
4.5	99
4	99.5
3.5	100
3	100.5
2.5	101
2	101.5
1.5	102
1	102.5
0.5	103

Table 6: UAD Apollo Controller to dBA SPL correlation scale. This was used to map the level of the current SPL via the read out of the level control of the Apollo Controller, previously calibrated to the tandem 10EaZy systems.

During the tests, visual checks on the 10Eazy Leq dBA readings were made to confirm that they correlated with the reference pink noise chart, and noted. At the end of each test session the tracks were replayed and the calibration between the pink noise reference and the level control setting checked. The reading from the controller was not visible to the participant but was visible to the tester via a software window on the Macbook Pro Laptop [Figure 36]. The Apollo controller level settings were marked on each test sheet and then converted to a dBA reading. This was then cross-referenced with the 10EaZy dB measurements. The relative difference between the readings of the preferred listening level in the INFRA and NORMAL conditions were calculated.

3.5 Test participants

15 members of The Prodigy "The Day is my Enemy Tour" [85] crew personnel were asked to participate in the test, along with local crew from the test venues. All participants reported that they had what they considered to be normal hearing.

3.5.1. Participant demographic

The participants were divided between professional and non-professional listeners. Professional listeners were deemed to be those with an advanced knowledge or interest in sound, and or, acoustics. These included the touring sound engineers and some members of the crew whose occupations were sound related, such as sound system technicians. Other participants were deemed non-professional unless they stated otherwise. Gender and age were also noted. Ages of the participants varied between 18 and 65 years. 33 participants were male, 5 female [Table 7].

Data was collected from a total of 38 participants over the three tests.

Birmingham : 5 participants (one participant's data removed from test at their request).
Wembley: 22 participants
Vilnius : 11 participants of whom two were control participants (data removed from test results).

Gender		Listener				Age		
Male	Female	Professional	Non-professional	18 – 24	25 - 34	35 – 44	45 – 54	55 – 65
30	5	15	20	3	10	11	9	2

Table 7: Participant in main test showing numbers by gender, age and listener type. Listener types were designated professional (sound engineer, audio professional) or Non-professional (others).

3.5.2. Control Participants

Two participants in Vilnius were chosen at random to be control subjects. Of these one was a professional listener the other not. When listening to the test they heard the same six tracks as the main test but no changes were made, no Infra-sub added. One participant had their results removed from the test at their own request.

3.6 Test Procedure

35 Participants contributed to the test data which was used to form the results of the test [Tables 14 & 15].

Tracks were played from within Apple Logic software [106] from an Apple Macbook Pro laptop via the Apollo Controller. Participants were given instructions prior to the test (See Appendix 1) that they should use the controller, when requested, to increase the volume from silent to a level (SPL) they preferred, one they thought was appropriate and satisfying for themselves. No indication as to what this level should be was given, other than that it should be their preferred listening level for music over a system of this nature. It was verbally stressed that there was no correct or incorrect level, and that it was a purely personal choice. Having chosen their preferred listening level (PLL) the participant was told to indicate this to the tester. The PLL was noted and the participants told to decrease the volume until it was inaudible. The process was then repeated with the next track.

4 Results

Initial preparation of the data involved comparing the differences in preferred listening levels (PLLs) in dBA SPL between the INFRA and NORMAL for each participant, for each of the six tests (See example Table 8). Results were then paired and the relative difference between the INFRA condition and NORMAL condition PLLs were calculated. The calculation of the preferred listening level differences (PLLD) produced three sets of figures for each participant, one for each music genre. The individual participant data is provided in Appendix 2 & 3.

ID	Pop Normal PLL	Pop Infra PLL	Pop PLLD	Dance Normal PLL	Dance Infra PLL	Dance PLLD	Rock Normal PLL	Rock Infra PLL	Rock PLLD
16	83	79	**4**	79	81	**-2**	86	86	**0**

Table 8: Example Table of a single participant's PLLD calculation derived from the six listening tests PLL data (Figures represent dBA SPL).

4.1 Test Data

The listening test data was coded for SPSS [107] along with genre (Pop, Rock, Dance), age group, listening type (professional, non-professional), gender and venue. The primary focus of data analysis was on the relative differences in dBA SPL of the PLL between the INFRA and NORMAL listening tests, the difference referred to as the PLLD.

Results of the PLL tests were analysed to examine whether they supported or disproved the hypothesis. This was done by an examination of the mean differences between the PLLs, the differences between PLLDs as well as a two way repeated ANOVA.

4.2 Control Group

The two control participants listened to the three music tracks twice each but no changes were made i.e., no Infra-sub was added. The control group was added to assess the consistency of achieving repeated preferred listening levels.

The control group provided evidence to support the robustness of the test [Table 9]. The control group had been given a test without any differences between the paired tests. If the test was robust it would be expected that there would be no differences in the PLL between each test in the pair, as listeners would be choosing the same PLL for each Genre grouped pair. If a JND was evident it would indicate that the choice of PLL was not determinate and would have questioned the validity of the test.

Listener Type	Age	PLLD Pop	PLLD Dance	PLLD Rock	Mean of Difference
Professional listener	25-34	0	0.5	-0.5	0
Non-Professional listener	25-34	0	-0.5	0.5	0

Table 9: Data from control participants. The dB SPL reading is the difference in level between the Normal and Infra listening test measurements (PLLD). A positive figure indicates PLL was higher for the NORMAL test compared to the INFRA test, conversely a negative number indicates PLL was lower for the NORMAL test compared to the INFRA test.

As Table 9 shows, the participants listened to each genre at PLLD's within ± 0.5dB SPL. The results indicate that PLLs were relatively similar when the test was repeated with no changes made. The differences in the PLLs is below the level of just noticeable difference (JND) (see section 2.4.6). Although not a statistically conclusive test it indicates that the participants were able to choose a PLL and return to a not noticeably different level (+/- 0.5dB SPL) later on in the test.

4.3 Listening Test

The combined listening levels of the NORMAL and INFRA test were compared. Table 10 shows the means of the sound pressure level measurements of the PLL tests in dBA, as well as the number of tests and standard deviation. The mean SPL of NORMAL test was 87.42 dBA. The mean SPL of the INFRA test was 86.64 dBA.

Test Type	Mean dBA SPL	N	Std. Deviation
NORMAL	87.42	105	6.59
INFRA	86.64	105	6.73

Table 10: Mean dB SPL of all tests showing mean averages of the NORMAL (without Infra-sub) and INFRA (With Infra sub) preferred listening test levels. N = Number of tests. The standard deviation is also shown. A difference of 0.78dBA can be seen between means.

The combined PLLD data from the tests was also studied. The PLLD data be seen in Figure 37, which shows a box and whisker plot of the data from the tests. The y-axis indicates the relative difference (PLLD) (in dBA SPL) between the INFRA and NORMAL. The 0 dB SPL line marked on the y-axis indicates no difference in SPL between the INFRA and NORMAL. Both the median and the first and third quartiles are above the 0dB line which indicates that the majority of participants 'PLL's' were lower for INFRA than NORMAL.

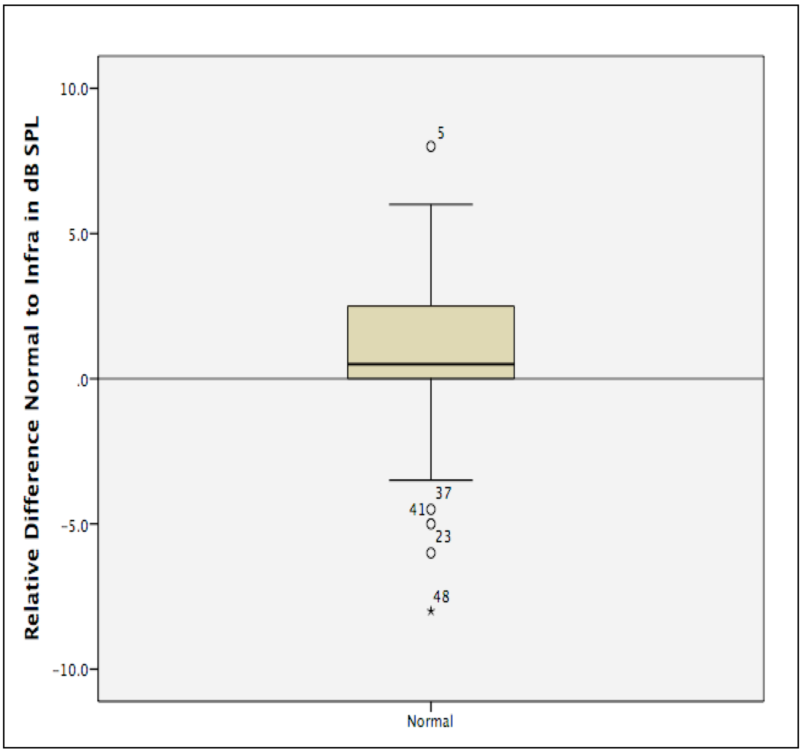

Figure 37: Box and Whisker chart showing distribution of data in percentiles. Figures are based on the individual relative difference levels of each participant. A positive number indicates that the track was listened to at a higher dB SPL without the Infra-sub (NORMAL), Outliers are signified with a circle for dance Genre, Rock Genre by a star. Numbers indicate test number for outliers.

4.4 Statistical Analysis

A statistical analysis was undertaken to examine the robustness of the data. A Two Way Repeated Measures ANOVA was chosen to analyse the data, the 'Two-Way” factors being Infra and Normal, the 'Repeated Measure” being that the same subject received both treatments. A standard ANOVA would have failed to model the correlation between the repeated measures, and the data would violate the ANOVA assumption of independence.

Due to the small sample numbers data was tested for normality, to check that the data-set was well modelled by a normal distribution, and to see if there was a possible violation of the normality assumption. Shapiro-Wilk's test was utilised.

Data was tested for sphericity using Mauchly's test. Sphericity is the condition where the variances between all combinations of related groups are equal. With a repeated measures ANOVA a violation of sphericity, where the differences between all the combinations of groups are not equal, would become too liberal (i.e., cause an increase in errors).

4.4.1. Effect of Infra Sub

A Two Way Repeated Measure ANOVA was run to determine the effect of Infra-sub on participants PLL's. There were no significant outliers, as assessed by examination of studentized residuals for values greater than ±3 standard deviations.

PLL's were normally distributed, as assessed by Shapiro-Wilk's test of normality on the studentized residuals ($p > 0.05$).

Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction, $\chi^2(2) = 3.58$, $p = 0.167$

Analysis of the ANOVA results show that participants chose a listening level significantly lower when infra-sub content is present, $F(1, 34) = 12.38$, $p = .001$ $\eta p2 = .267$.

This supports the hypothesis that increasing the low frequency content below 50Hz, the region referred to as “Infra-Sub”, the participant would listen to the same musical material at a lower dBA sound pressure level.

4.4.2. Effect of Genre

A Two way Repeated ANOVA was run to determine the effect of musical genre on participants preferred listening levels, $F(2, 68) = 18.88$ $p < 0.001$, $\eta p2 = .357$.
The ANOVA indicated that genre had bearing over the participants PLL. This is discussed more fully in section 5.5.1

Summary: Rock and Pop music genres had a greater difference of PLL's between the NORMAL and INFRA listening tests, although dance music still represented a statistically significant difference.

The interaction between INFRA/NORMAL and Genre was not significant, $F(2, 68) = 1.297$, $p > 0.05$.

Summary: although between music genres there was some difference between participants PLL's these did not have a statistically significant impact on the test.

Figure 38 shows a box and whisker plot of the PLLD's from the participants tests by genre. The y-axis indicates the PLLD in dBA SPL between the INFRA and NORMAL tests. The 0 dB SPL line indicates no difference in SPL between the INFRA and NORMAL PLL tests. The median line of each genre is equal to or above the 0dB line which indicates that the majority of participants PLL were lower in the INFRA test, when the Infra-sub content was present, than in the NORMAL. The difference is most noticeable in the Rock genre. There are several outliers in the Dance genre which are discussed in section 4.5.3.

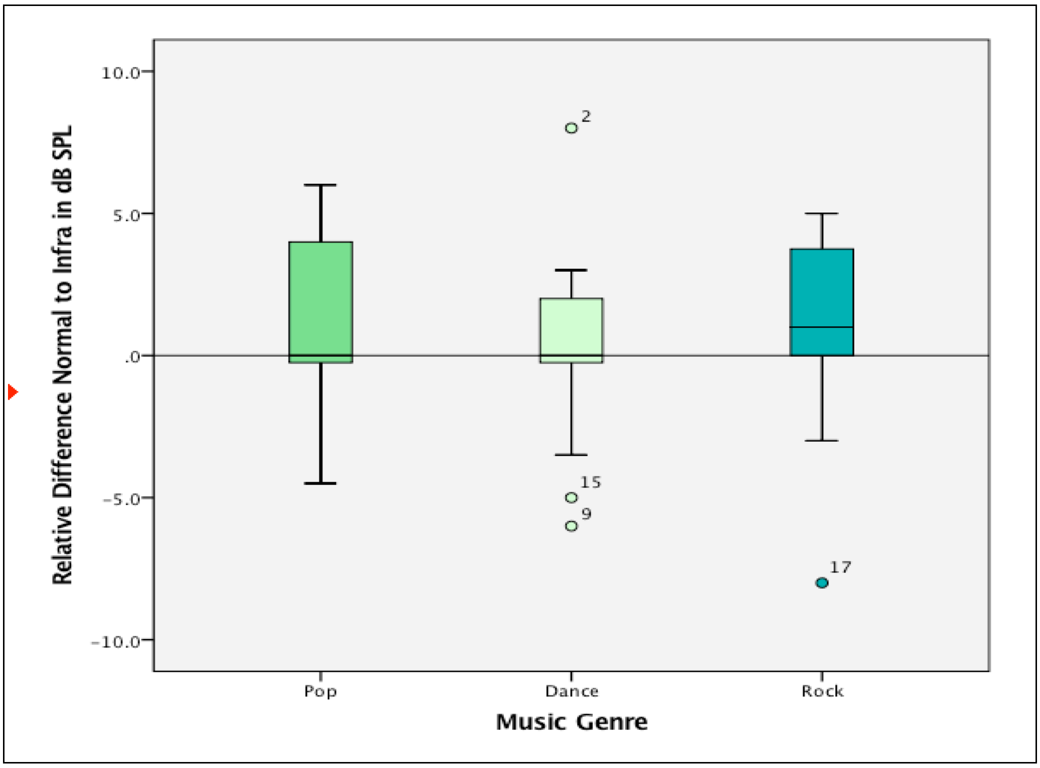

Figure 38: Box and Whisker chart showing distribution of data in percentiles. Differences NORMAL to INFRA data split by Genre. Figures show individual relative difference between INFRA and NORMAL Listening tests of the PLL's of each participant. A positive number indicates that the track was listened to at a higher dB SPL without the Infra-sub (NORMAL). Numbers indicate participants test number for outliers.

Table 11 shows the Means of the PLLD's grouped by Genre, the difference in dB SPL between the INFRA and NORMAL listening tests preferred listening levels . As can be seen the SPL is above the JND in Rock and Pop genres but below in Dance. A positive PLLD represents that the dB SPL PLL of the NORMAL condition was greater compared compared to that of the INFRA condition.

	PLLD Pop	PLLD Dance	PLLD Rock
Mean	1.129	0.029	1.143
N	35	35	35
Std. Deviation	2.4294	2.8747	2.7589

Table 11: Means of PLLD by Genre. The mean represents the PLLD (difference in dBA SPL between the INFRA and NORMAL listening tests preferred listening level) by genre. As can be seen the level is above the JND in Rock and Pop genres but not in Dance.

4.5 Discussion

As can be seen in the data produced and shown in Table 10, the overall mean SPL of the PLL chosen by the test participants in the Normal Test (without Infra-sub) was 87.42dB. The mean SPL of the PLL chosen by the participants in the Infra Test (with the addition of the Infra-sub) was 86.64dB, a difference of 0.77dB. When the combined mean of both the INFRA and NORMAL data of 87dB is correlated to the graph in Figure 23, of JND compared to SPL, it is noted that the level of the JND is > 0.54dB. The difference between the INFRA and NORMAL tests, being 0.78dB is greater than the JND. The SPL of the PLL chosen by the participants during testing is, on average, noticeably lower, the PLLD being greater than the JND, when listening with the Infra-sub addition. This result supports the hypothesis that the PLL will be significantly lower statistically and perceptually when the low frequency content (Infra-sub) of audio material is increased, notably in the genres Pop and Rock where the mean difference was greater than 1dB.

4.5.1. Between Genre Differences

The differences between genres were less marked between the Rock and Pop genres with greater comparative differences being seen between the Dance/Pop and Dance/Rock genres. A possible reason for the greater differences can be seen in a comparison of the level of the three genre tracks in Table 12. All three tracks have a a similar mean SPL ± 1.5dB in the low frequency region 30 – 80Hz. However above 80Hz the mean averages between 90 -12000Hz are 1.35dB between the Pop and Rock categories but > 9dB between the Dance and Pop/Rock categories. The difference in dBFS above 80Hz indicates that in comparison the dance genre track has a greater level in dBFS below 90Hz compared to other frequencies in its overall frequency spectrum. Whilst the Pop and Rock tracks exhibit a level difference of <1.5dBFS between the ranges 30-80Hz and 90-12000Hz, the Dance track shows the frequency region between 30- 80Hz as being significantly louder by > 7.5dB than the region between 90-12000 Hz.

Genre	Mean 30-12000Hz	Mean 30-80 Hz	Mean 90-12000Hz
Pop	-38.2	-39.2	-37.95
Dance	-46.6	-40.7	-48.35
Rock	-39.6	-40.7	-39.3

Table 12: Comparison of mean SPL of the three tracks by genre. It can be seen that the Pop and Rock tracks have a similar SPL of <1.5dB. The dance track has a greater difference with the frequencies below 80Hz being greater than 7.5dB louder.

The listening tests were all performed using recorded music. Recorded music has been through several stages of dynamic compression, firstly in the recording process and then again in the mastering process. Recorded music can therefore have a potentially smaller dynamic range than a live concert where the use of extreme levels of dynamic control are less prevalent. Recordings have in recent years been subjected to an increasing amount of 'multi-band compression'. Multi-band compressors identify frequency ranges in the original signal using frequency analysis. This analysis is used to compress or expand at the frequencies set by the mix engineer [108]. These tools are now primarily software based [109]. Mixes have been increasingly compressed using multi-band compression and similar techniques to maximise their perceived level. This has been popularly described as the 'loudness war' and is defined by the respected sound engineer Bob Katz in his influential book “Mastering Audio: The Art and the Science” [110] as “*a term applied to the ongoing increase in the loudness of recorded music, particularly on Compact Discs, as musicians, mastering engineers and record companies apply dynamics compression and limiting in an attempt to make their recordings louder than those of their competitors*”.

The interaction between perceived loudness and frequency has become an intrinsic part of modern music production. The final mastered version of a track, particularly in regards to broadcast listening (radio or internet streaming), has seen a shift in mastering techniques to producing recordings that may be perceived to be louder [111].

Katz describes the techniques of mastering audio recordings, including the use of dynamic compression to maximise the level that can be captured by the recording medium. He also details the problems of restriction of the frequency bandwidth to conform with the limitations of the Compact Disc Digital Audio 'Red Book” Standard IEC 60908 [112], the frequency range of a CD being limited with high and low pass filtering being imposed during both the recording and mastering process and by the sampling frequency of 44.1kHz.

The dynamic range of the excerpts was measured using TT Dynamic Range Meter[113]. The chosen genre tracks varied between:

Dance: 4.98 dB

Pop: 6.94 dB

Rock: 8.67 dB

The dance track has been subjected to the greatest amount of loudness processing as can be seen in its restricted dynamic range. The maximum level available has been reserved for the low frequencies as seen in Table 12.

The spectral balance of the dance track would therefore likely promote mechanosensation at a lower dBA SPL than the other two tracks, as the Infra Sub content is already higher in relation to other frequencies in the track.

4.5.2. Between Venue Differences

The testing took place at three different venues over four separate dates. Four tests were conducted in Birmingham, twenty-two over two days in Wembley and eleven in Vilnius. The smaller sample numbers may account for the different spread of data by venue, but in the majority of tests the data supported the hypothesis. Due to time restrictions it was impossible to conduct all the tests at a single venue. The decision to use venues of similar capacities and sizes was made so the data would show greater correlation than if a disparate selection of venues had been chosen. As many factors were replicated as possible within the confines of the venue/touring scenario. It can be noted that the Vilnius Arena produced very positive data to support the hypothesis. Wembley and Birmingham produced positive data in two of the three genres, and less conclusive data in the third. This varied between Birmingham (Rock) and Wembley (Dance). Considering the small sizes of test groups, especially in Birmingham (four), it is difficult to draw conclusions from the comparison of data between the individual test venues but it is not considered that any differences had a significant effect on the tests (Figure 39).

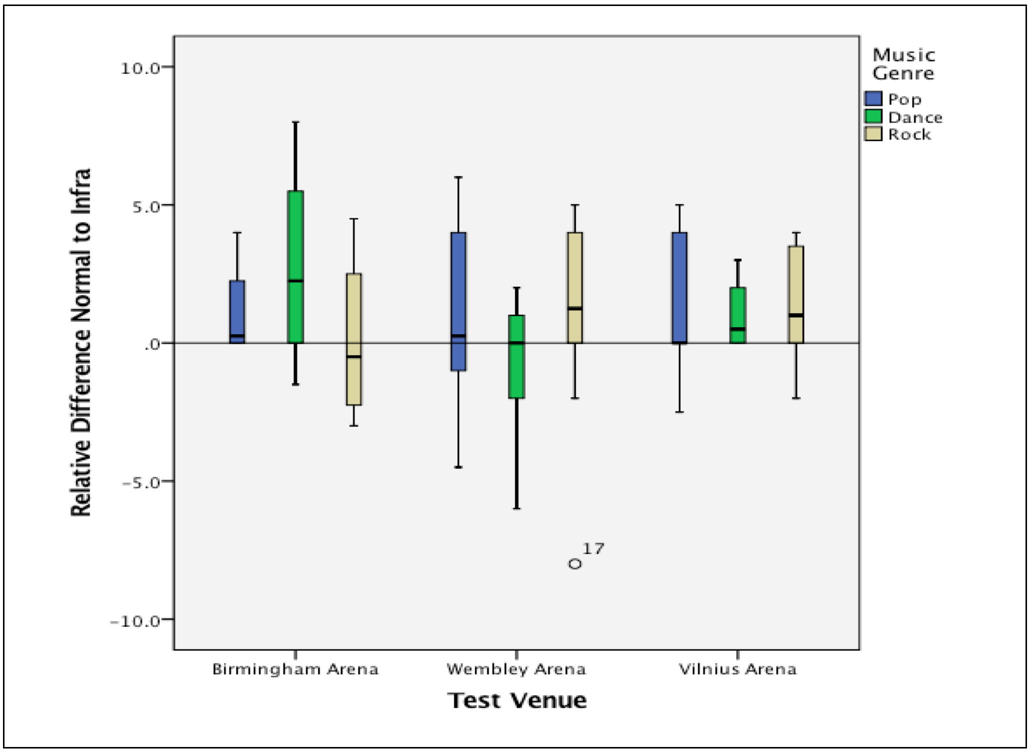

Figure 39:Box and Whisker chart showing distribution of data in percentiles. Relative difference between INFRA and NORMAL by Genre and by Venue sub sets. Figures based on the PLLD's of each participant. A positive number indicates that the track was listened to at a higher dB SPL without the Infra-sub (NORMAL). It can be noted that the Vilnius Arena produced very positive data to support the hypothesis. Wembley and Birmingham produced positive data in two of the three genres. Numbers indicate test number for outliers.

Figure 39 shows a Box and Whisker plot of the PLL differences from the participants tests separated by genre and venue. The Y axis indicates the relative difference of the PLLl in dBA SPL between the INFRA and NORMAL PLL tests. The 0dB SPL line marked on the y-axis indicates no difference in SPL between the INFRA and NORMAL PLL tests. The median line of each genre is equal to or above the 0dB line except in the Dance Genre at Birmingham Arena where it is below. which indicates that the majority of participants PLL's were lower in the INFRA test, when the Infra-sub content was present, than in the NORMAL, when it was not. The median and the first and third quartiles are above the 0dB line in all three genres in Vilnius Arena. The median and the first and third quartiles are above the 0dB line in two of the three genres in Birmingham Arena (Pop and Dance) and Wembley Arena (Pop and Rock).

4.5.3. Test Comment

Each participant was de-briefed following their test session and the experiment explained to them along with the hypothesis. The majority of non-professional listeners were unaware of the acoustic differences between the INFRA and NORMAL tests although most commented that one pair of tracks sounded 'fuller' or 'bigger', there were no comments that stated that the sound had too much 'bass' content. This possibly implies that the Infra-sub was not considered as part of the 'bass' spectrum. With the professional listeners the majority (13 of 15) were able to perceive the sonic differences. One sound engineer commented that he enjoyed the Infra-sub extension so much he found it encouraged him to listen to one of the tracks considerably louder (+8dB) as '*It sounded so good*" (Participant ID 17). The 'sounded better' comments were echoed by participants ID 15 and ID 9 both of whom were non-professional listeners but enjoyed listening to the dance track louder with the Infra-sub added. These comments explain the outliers that can be seen in the box and whisker chart in Figure 38. The general consensus of opinion was that the extended low frequency, when noted by a participant, was seen as a positive addition. Only on two occasions did this result in a higher PLLD, notably in the outliers mentioned previously which did affect the averaged PLLD.

5 Conclusions

The results of the combined test results support the hypothesis. The PLLD was above the JND between the INFRA and NORMAL. Statistical analysis of the data indicates a greater than 95% probability that the lower PLL is due to the effect of the added infra-sub content. Increasing the low frequency content below 50Hz, the region referred to as “infra-sub” can be used to lower PLL's. This research adds to the understanding of the positive contribution Infra-sub can have to PLL, which in turn can be a factor in decreasing overall dBA SPL's.

Practical application of the addition of infra-sub content has been proved in these tests with the use of the D&B Infra speaker cabinets, producing an extension of the low frequency range of the speaker system as well as an increase in SPL (Figure 33). For the sound engineer, infra-sub can be integrated into existing systems, and utilised as a tool to help significantly reduce overall A-weighted SPL readings in an arena environment. It is proposed that Infra-sub content if introduced into open-air festival situations would produce similar results.

For the audience Infra-sub content can help maintain a preferred listening experience but at lower dBA SPL. In events where maintaining a pre-determined SPL is critical, such as arenas and open air festivals, infra-sub will contribute to audience satisfaction ratings whilst minimising the affect of environmental noise. Low frequency extension can also result in an improvement in the listening experience. Whilst making objective evaluation listening tests of high end HiFi loudspeakers designer Floyd Toole [114] noted a correlation when comparing speakers fidelity scores:

“*The average bass extension - the low-cutoff frequency - progressively decreases as the fidelity rating increases.*” He concluded that “*The listeners liked low bass - not more bass, in the sense that it is boosted, but bass extended to lower frequencies*” .

Further study into audience PLL would benefit from analysing the low frequency extension provided in the infra-sub addition, a topic that was only touched on in this study, in the post test de-briefing (see section 4.5.3).

Decreasing SPL has health implications due to the subsequent reduction in noise exposure. As Çelik, Yalçın, and Öztürk [115] note; the “*greater sensitivity of the human ear between the range 1–5kHz, probably relating to the outer and middle ear characteristics where mid range frequencies are emphasised, increases the likelihood of hearing damage in this range*.”

"*Sensorineural hearing loss produced as a result of high noise level depend upon not only exposure time but also some features of noise (i.e. frequency, intensity and other characteristics of noise)*".

The region of 1-5kHz where the ear is most sensitive is emphasised in the A weighted loudness curve (as discussed in Section 2.2.2.). Lowering the overall dBA SPL contributes to minimising the chance of hearing damage [99].

5.1 Applications and Impact

With a greater understanding of the effect of Infra-sub on the listening experience speaker systems can be designed, or adapted, to not just provide their current primary role as bass extension, but also produce greater whole body vibration.

5.1.1. Systems Development

Development of low-frequency cabinets suitable for delivering the range needed to extend below 50Hz has increased in recent years. Many sound reinforcement loudspeaker manufacturers already produce cabinets that have an extended low frequency range, but advances in digital amplification are increasing the practicality of their designs. Developments in driver technology have led to more efficient transducers. Moving magnet linear motor drivers such as the Powersoft 'M-Force" [116] has led to an increased interest in speaker manufactures such as Funktion One designing cabinets to utilise the M-Force technology, [117].

D&B Audiotechnik have led the way with the introduction of an integrated Infra-subwoofer speaker cabinet in it's J-Series Speaker range [118]. The J-Series Infra cabinets commercial success will likely influence the adoption of specialist infra-subwoofer speaker cabinets into the systems of other major manufacturers. The use of an infra-subwoofer cabinet sees large format array systems move from a four-way system to a five-way cross-over system, low and high pass filter development being sculpted to maximise the impact of infra-sub. Further investigation into Infra-sub is needed to pinpoint the most effective frequency bandwidth for the stimulation of WBV utilising these specialist speaker cabinets.

The use of speakers designed to reproduce infra-bass is already starting to become more widespread as they are gradually being integrated into system designs as can be seen in Table 13, a cross section of European festivals in 2016.

Festival	Manufacturer	Speaker System Main Stage	Infra Sub
Greenfield Festival, CH	D&B Audiotechnik	J Series Line Array	D&B Infra
Mad Cool, ES	Adamson	E15 Line Array	
Hurricane Festival, DE	D&B Audiotechnik	J Series Line Array	D&B Infra
Southside Festival, DE	D&B Audiotechnik	J Series Line Array	D&B Infra
Volt Festival, HU	JBL	VTX Line Array	
Jarocin Festival, PL	L'Acoustic	V'Dosc Line Array	
Ollesummer, EE	L'Acoustic	K1 Line Array	
Pohoda Festival, SK	JBL	VTX Line Array	
Dour Festival, BE	Adamson	E15 Line Array	
Biarritz Festival, FR	JBL	VTX Line Array	
Q Stock, FI	JBL	Vertec	
Chiemsee, DE	D&B Audiotechnik	J Series Line Array	D&B Infra
Home Festival, IT	D&B Audiotechnik	J Series Line Array	

Table 13: Sample Cross section of Major European Festival Sound Reinforcement Systems 2016 (samples chosen from European festivals, established more than 5 years, with audience capacity on main stage >10k).

5.2 Future work

The importance of mechanosensation should be further investigated in relation to the musical experience. Floyd Toole makes a critical point: "*low bass - not more bass*" "*extended to lower frequencies*"[108] . Low frequency extension does not necessarily contribute to what would be considered the musical content of the bass register, as it falls below that in terms of the tonal range of most instruments [100]. Although we cannot always determine tone at these frequencies we can perceive them [119]. As the Infra-sub content used was a combination of increased SPL of low frequencies combined with an extension of the low frequency range, it is impossible to calculate which of these makes the greatest contribution to lowering the PLL. Further testing should include separating these two factors and assessing their individual impacts.

The format and style of this test was practical and real-life based. Further testing would benefit from a more acoustically controlled environment [120]. Many Arenas, like Wembley (a converted swimming pool), were not built as music venues and subsequently have poor acoustics with long reverberation times, especially in the low frequencies. A modern purpose built music venue or large production rehearsal studio would provide a more appropriate test site [121]. Awareness of the importance of arena acoustics in helping to provide a better audience experience is increasing. This has been seen in the Netherlands with the work of Lautenbach, Heringa, and Vercammen [107]. Venues are introducing variable acoustic dampening that can decrease the long reverberant times that provide a positive contribution to the crowd noise and atmosphere at sporting events, to the shorter times more suitable for amplified music events [122]

A wider range of musical excerpts with wider dynamic ranges would provide a better simulation of a live performance. Modern recorded commercially released tracks and their use of current production techniques differ in dynamic range from live concert performance where the use of mix compression, which reduces the dynamic range, is rare [123]. Mix compression and limiting at concerts tends to be of an overload protection nature, designed to reduce component damage, rather than used as a creative tool. Channel compression, on individual or groups of instruments is common in live sound engineering however mix compression is not. Further testing should be based on program material with a dynamic range more comparable to that of a live concert performance.

Bespoke hardware and software for analysing low frequency content would improve the quality and reliability of data.

As noted previously, dividing the two experiences of 'mechanosensation' and 'low frequency range extension' is needed to more extensively explore the topics raised in this paper. The effect of airborne WBV has many implications on the way we perceive sound. The involving quality that mechanosensation provides is a subject that has only been touched on in this paper.

"As a surprise to most people (even to many acousticians)" comment Moller and Pederson (2004) "*humans can perceive sound at least down to a few Hertz. This applies to all humans with a normal hearing organ, and not just to a few persons."* [98].

5.3 Personal Comment

The subject of this dissertation is the product of many years of consideration by myself as a professional sound engineer. The idea of using very low frequency sounds (<30Hz) to provide a better audience experience was first discussed by myself and Jason Baird [124] of Martin Audio in 2008. This resulted in the use of 12 Martin Audio prototype infra-subwoofer cabinets to supplement the festival system at the 2008 V Festival [125] . Permission from the festival organisers was sought and the need for 60,000 watts of extra speaker amplification, to make the performance 'quieter' explained. Support for this original idea was provided at the time by Jim Griffiths of Vanguardia [126] who were noise consultants for the festival. Although no hard empirical data is available from this event the opinion of myself, Baird and Griffiths was that a positive result was achieved.

Following on from 2008 I have continued to explore the practical application of infra-sub both at open-air festivals and indoor arenas. Although the gains may only be in region of 1-2 dB this is greater than JND and therefore perceptible, which is why this approach appears to be successful. In my personal experience this has contributed to a more satisfying experience not just for myself as the sound engineer, but also for the audience [127].

6 Appendix

6.1 Listening Test Instructions

Listening Test Instructions
Please read carefully before beginning the test

You will be asked to listen to six tracks over the sound system. You will be given a controller to increase the volume from zero, to a level you prefer, one that you feel is appropriate and satisfying for listening to music over a sound system of this size and nature.
Please note that there is no correct or incorrect level, it is purely a personal choice, the level you prefer.

Each musical segment will last 60 seconds. You will be advised when they start and when to bring up the level. Once you are happy with the level you have chosen please signal to the tester and return the control to zero. The tester will then move on to the next track.

Please remember there is no right or wrong level it is purely your preferred level.

Please let the tester know of any thoughts you have, negative or positive, after the test has been completed.

Thank you for your assistance.

6.2 Data

ID	Gender	Profession	Age	Venue	Pop PLLD	Dance PLLD	Rock PLLD
1	Male	Non-professional	45-54	Birmingham Arena	0.0	1.5	4.5
2	Male	Non-professional	45-54	Birmingham Arena	4.0	8.0	-3.0
3	Male	Professional Listener	18-24	Birmingham Arena	0.5	-1.5	-1.5
4	Male	Professional Listener	35-44	Birmingham Arena	0.0	3.0	-0.5
6	Male	Non-professional	45-54	Wembley Arena	4.0	0.0	0.0
7	Male	Non-professional	45-54	Wembley Arena	-2.5	-1.5	0.5
8	Male	Professional Listener	45-54	Wembley Arena	2.0	0.5	-0.5
9	Male	Non-professional	45-54	Wembley Arena	6.0	-6.0	4.5
10	Male	Non-professional	45-54	Wembley Arena	4.0	2.0	3.0
11	Male	Professional Listener	18-24	Wembley Arena	1.0	2.0	0.0
12	Male	Professional Listener	18-24	Wembley Arena	2.0	-3.5	5.0
13	Male	Professional Listener	45-54	Wembley Arena	0.0	-2.5	3.5
14	Male	Professional Listener	25-34	Wembley Arena	-4.5	0.5	-2.0
15	Male	Non-professional	55-65	Wembley Arena	4.0	-10.0	1.0
16	Male	Non-professional	45-54	Wembley Arena	4.0	2.0	0.0
17	Male	Professional Listener	35-44	Wembley Arena	2.0	2.0	-8.0
18	Male	Professional Listener	25-34	Wembley Arena	2.0	0.0	-0.5
19	Female	Non-professional	35-44	Wembley Arena	0.0	-2.0	4.0
20	Female	Non-professional	25-34	Wembley Arena	0.0	0.0	3.0
21	Male	Non-professional	35-44	Wembley Arena	0.0	0.0	2.5
22	Female	Non-professional	25-34	Wembley Arena	4.0	2.0	-1.0
23	Male	Professional Listener	35-44	Wembley Arena	0.5	0.0	4.0
24	Male	Professional Listener	35-44	Wembley Arena	-1.0	-2.5	5.0
25	Male	Non-professional	35-44	Wembley Arena	-0.5	0.5	1.5
26	Female	Non-professional	25-34	Wembley Arena	-2.5	0.0	4.5
27	Male	Professional Listener	25-34	Wembley Arena	-1.0	-0.5	0.0
28	Male	Non-professional	25-34	Vilnius Arena	4.0	0.0	3.5
29	Male	Professional Listener	25-34	Vilnius Arena	-0.5	2.0	0.0
30	Male	Professional Listener	55-65	Vilnius Arena	0.0	0.5	1.0
31	Female	Non-professional	35-44	Vilnius Arena	1.0	0.0	0.5
32	Male	Professional Listener	35-44	Vilnius Arena	0.0	0.0	-2.0
33	Male	Non-professional	25-34	Vilnius Arena	1.0	1.5	1.0
34	Male	Non-professional	35-44	Vilnius Arena	-2.5	0.0	4.0
35	Male	Non-professional	35-44	Vilnius Arena	4.5	0.0	2.5
36	Male	Non-professional	25-34	Vilnius Arena	4.0	3.0	0.0

Table 14: Preferred Listening Level Test Data showing Participant ID Number, Gender, Listener Type, Age Group, Test Venue, PLLD by Genre NORMAL to INFRA (Positive number indicates PLL was greater in NORMAL listening tested compared to INFRA listening Test).

ID	Pop Normal	Pop Infra	Dance Normal	Dance Infra	Rock Normal	Rock Infra
1	97.0	97.0	97.5	96.0	101.0	96.5
2	81.0	77.0	85.0	77.0	83.0	86.0
3	92.0	91.5	90.5	92.0	92.0	93.5
4	104.0	104.0	102.0	99.0	102.5	102.0
6	85.0	81.0	82.0	81.0	85.0	85.0
7	88.5	91.0	85.0	86.5	91.0	90.5
8	92.5	90.5	87.0	86.5	94.5	95.0
9	91.0	85.0	87.0	93.0	99.0	94.5
10	85.0	81.0	81.0	79.0	86.0	83.0
11	86.0	85.0	85.0	83.0	85.0	85.0
12	87.0	85.0	83.0	86.5	88.0	83.0
13	93.0	93.0	92.0	94.5	92.5	89.0
14	88.0	92.5	88.0	87.5	91.0	93.0
15	83.0	79.0	75.0	85.0	87.5	86.5
16	83.0	79.0	81.0	79.0	86.0	86.0
17	92.5	90.5	96.5	94.5	89.0	97.0
18	85.0	87.0	86.0	86.0	88.0	88.5
19	77.0	77.0	77.0	79.0	79.0	75.0
20	83.0	83.0	82.0	82.0	86.0	83.0
21	81.0	81.0	79.0	79.0	89.5	87.0
22	79.0	75.0	79.0	77.0	86.0	87.0
23	89.0	88.5	86.0	86.0	93.0	89.0
24	77.0	78.0	70.0	72.5	75.0	70.0
25	86.5	87.0	92.5	92.0	92.5	91.0
26	72.5	75.0	75.0	75.0	77.0	72.5
27	90.0	91.0	90.0	90.5	92.0	92.0
28	93.0	89.0	92.5	92.5	97.0	93.5
29	87.5	88.0	90.0	87.5	88.0	88.0
30	90.5	90.5	88.5	88.0	93.0	92.0
31	86.0	87.0	85.0	85.0	86.5	86.0
32	79.0	79.0	79.0	77.0	81.0	83.0
33	91.0	90.0	92.5	91.0	93.5	92.5
34	96.5	99.0	94.0	94.0	97.5	93.5
35	90.0	85.0	86.0	86.0	90.5	86.5
36	85.0	81.0	86.0	83.0	86.5	86.5

Table 15: Preferred Listening Level Test Data showing Participant ID and PLL(in dBA SPL) by Genre, NORMAL and INFRA Listening Test Results.

Table 16: Hand Held Meter Level checks Wembley.

Levels taken with hand held meter using 50Hz tone meter set to slow response C weighting.

Wembley Level Check – Subwoofers		
@50Hz		
Position	Prediction	Measured
FOH	99-102	99
Array Left 5m	105-108	104
Array Left 15m	102-105	102
Array Right 5m	105-108	104
Array Right 15m	102-105	101
Array Centre 5m	108-111	107
Array Centre 15m	102-105	101

7 Glossary of Terms & Abbreviations

ArrayCalc:	Proprietary software used to design loudspeaker systems, calculating mechanical speaker angles, cabinet placement and SPL predictions of coverage.
B2:	Low Frequency Speaker (Subwoofer) Cabinet manufactured by D&B Audiotechnik.
CSA:	Cardioid Subwoofer Array. Speaker system that utilises a second rear facing sound source to cancel energy at the rear of the cabinet and to increase directivity.
Clarity:	The qualitative concept of the ability of the listener to hear and understand speech, to follow the nuances of pitch, timbre, and rhythm in a coherent way.
Critical Distance:	The distance at which the sound pressure level of the direct sound and the reverberant sound are equal when dealing with a directional source.
Cross-over:	A device that splits a signal into different frequency bands e.g. Bass, Mid and High, which are then fed to the different components of the speaker system.
dBA:	Decibels measured using the 'A' weighted measurement scale.
dBC:	Decibels measured using the 'C' weighted measurement scale.
dBFS:	Decibels relative to the full scale. This is a measurement term used in digital systems to indicate decibel level where there is a defined maximum available level, denoted as 0 dBFS. A level of -6dBFS would represent a signal that reaches 50% of the maximum possible digital level.
EDM:	Electronic Dance Music.
FOH:	Front of House. In this document the term is used to describe the position of the mixing desk from where the sound is controlled in a venue. It is usually centrally placed and in a festival situation typically 30-40m from the downstage edge.
INFRA :	This term when capitalised in this document refers to the listening test that included the extra Infra-sub content. Conversely NORMAL indicates the test that did not have the extra Infra-sub content.
Infra-sub:	In this document the term is used to describe frequencies below 50Hz.
Involving:	In this document this term is used in the context of participation, and

	refers to a sense of being part of an experience, 'the concert or festival', and in particular the music.
ISO:	International Organisation for Standardisation.
J-Infra:	Low Frequency Speaker (Subwoofer) Cabinet manufactured by D&B Audiotechnik
JND:	Just Noticeable Difference. The amount something must be changed in order for a difference to be noticeable, detectable at least half the time. Also referred to as DL or Difference Limen. For the purposes of this experiment a JND of 0.54 dB SPL was used.
LAeq:	Leq measurements made using the A weighting scale. Represented either a LAeq or with the weighting suffixing the dB level e.g. LAeq = 72dB or Leq = 72dBA
Leq:	Leq is used to describe sound pressure levels, such as music, that vary over time. It results in a single decibel value that takes into account the total sound energy over the period of time measured e.g Leq = 72dB.
Line Array:	A line array is a group of omnidirectional radiating elements arrayed in a straight line, closely spaced and operating in phase with equal amplitude. Points on axis of the array exhibit constructive interference, and the sound pressure increases by 6 dB relative to a single unit. At other points off axis, path length differences produce cancellation due to destructive interference resulting in a lower sound pressure level. Modern 'line arrays' combine this characteristic with waveguide elements for the high frequencies which beam form these frequencies. The constructive interference of the low frequencies are aligned to the high frequencies so that the resulting arrayed system provides consistent coverage in front of the array.
NORMAL:	This term when capitalised in this document refers to the listening test that did not include the extra Infra-sub content. Conversely INFRA indicates the test that did include the extra Infra-sub content.
Pink Noise:	Pink noise is filtered white noise noise where the power spectral density (energy or power per Hz) is inversely proportional to the frequency of the signal). Each octave (halving/doubling in frequency) carries an equal amount of noise energy. It derives it's name from the colour produced when white light is filtered using the same technique.
PLL:	Preferred Listening Level. The SPL that listeners preferred during INFRA and NORMAL listening tests expressed in terms of dBA SPL.
PLLD:	Preferred Listening Level Difference. The difference between the

	INFRA and NORMAL test PLL of individual listeners expressed in terms of dBA SPL. A positive number indicates that the NORMAL Test PLL was higher than the INFRA Test PLL. A negative number indicates that the INFRA Test PLL was higher than the NORMAL Test PLL.
Point Source Array:	A point source cabinet has all the speaker components aligned so the sound appears to come from a single point (or source). When arrayed the cabinets are aligned to a single point. Usually trapezoidal shaped cabinets are used so when placed next to one another they will assume the correct angles.
Schroeder Frequency:	The frequency at which in a space, such as a room, the sound changes from being diffused (above) to resonant (below). Sound wavelengths that match the rooms dimensions will resonate.
Spectral Colouration:	Changes to the amplitude and intensity spectrum of a musical sound or complex noise.
SPL:	Sound Pressure Level.
Subwoofer cabinet:	Speaker cabinet designed to reproduce only low-frequency sound.
Supraliminal:	Above the threshold of sensation.
Temporal Smearing:	Changes in the time domain or phase of a musical sound or complex noise.
V'Dosc:	Large Format Line Array system manufactured by L'Acoustics.
WBV:	Whole Body Vibration. Mechanical vibrations that excite large parts of the body via sound waves or the vibrations of a contact surface.

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