THE EFFECT OF SEATS ON THE CALIBRATION OF CINEMA SOUND SYSTEMS

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1 INTRODUCTION

The standardisation of loudspeaker responses in cinema reproduction is necessary for maintaining consistent perception of the soundtracks from one theatre to another. For this reason, individual, *in situ* corrections are usually made to loudspeaker-system outputs in each room, but research has shown that the recommended calibration practices may be affected by the proximity of the microphones to the seats in ways that are objectively and subjectively different.[1] This paper aims to assess the impact of seats in both objective and subjective terms, and to determine whether changing the microphone height when calibrating the systems can lead to a more consistent perception of the sound quality. A measurement microphone and dummy head were used to assess the sound field and obtain listener preferences, respectively, in three different venues. The acoustic disturbances due to the seats are noted for all three cases, and in each show a decreasing significance with height above the seats.

2 LITERATURE SEARCH

Prior to embarking on the latest study, a literature search was undertaken to help determine to what degree the seats were known to change the characteristics of any sound arriving from the front of a theatre. Two 1964 papers coined the term 'seat-dip' to describe the selective attenuation of low frequencies (LF) when the sound grazes audience seating.[2, 3] The effect is attributed to the cavities between seat rows as the direct sound grazes across seat rows, diffracts, and then reflect off the floor between rows.[4] The reflexions then destructively interfere with the direct sound, disturbing the low-frequency response.[5]

Schultz and Watters measured four concert halls, as shown in Figure 1, determining that the frequency of maximum attenuation-dip mainly depends on seat back heights.[2] This was later confirmed by Bradley.[7] The degree of attenuation also depended on the height above the seats, and it was found that the disturbance due to the seats was negligible above about 4 metres, as shown in Figure 2.[2, 7] Similar findings were made by Sessler and West, as shown in Figure 3.[3]

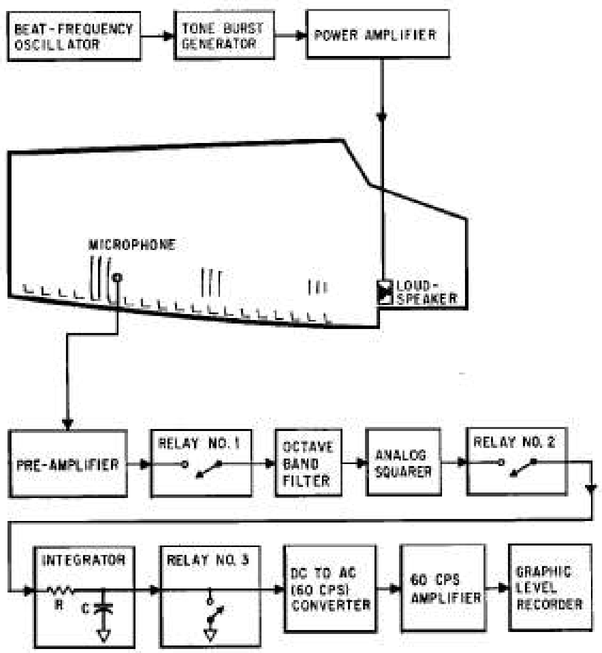


FIG.1 . Block diagram of pulse-measuring equipment; for description of operation, see Sec. II in the text.

Figure 1 - Early technique for measuring the seat dip effect (from [3])

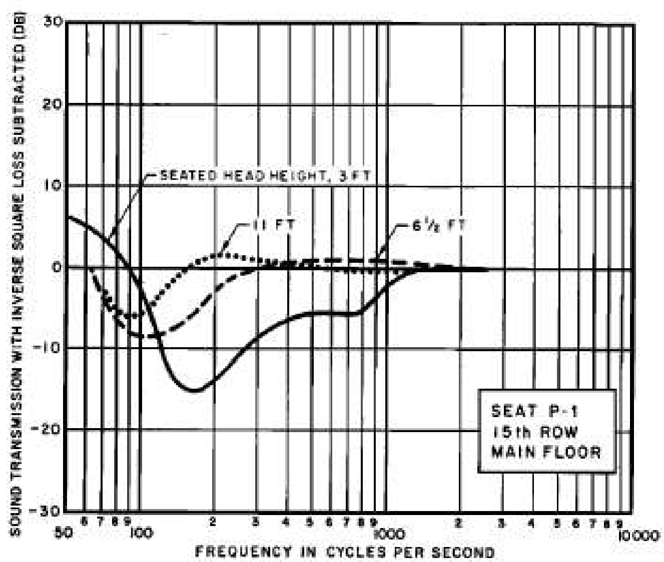


FIG. 9. Transmission characteristics of the direct sound for various heights above a single seat on the main floor of La Grande Salle, Montréal. The microphone was moved from seated head height at this position to heights of 6½ and 11 ft, respectively, above the seat. The dashed curve of Fig. 8, at 14-ft height, may be regarded as complementary to these data.

Figure 2 - Seat dip variance with height (from [3])

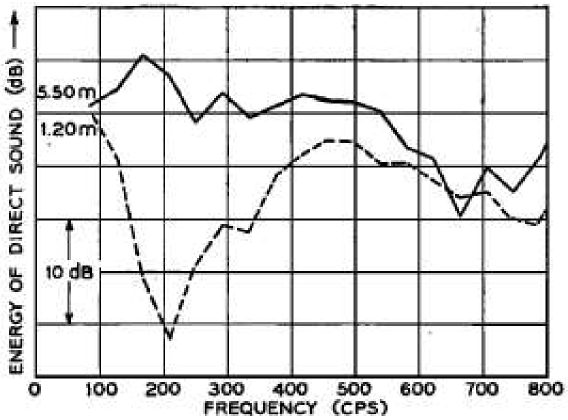


FIG. 7. **Energy of the direct sound at ear level and at an elevated position in the hall. Parameter: elevation above the main floor in meters.**

Figure 3 – Seat dip variance with height (from [4])

The centre frequency of the dip was later shown to vary from where the seat height was about ¼ wavelength to approximately one octave above this, depending on the vertical angle of incidence and number of paths available under the seating.[6] The seat-dip frequency-band typically remains within the 100 - 300 Hz range, with resulting attenuation of up to 20 dB.[3, 5, 6, 8] It has also been shown that the presence of an actual audience has little effect below 800 Hz.[3, 4]

Davies and Lam presented evidence of the dependency on receiver height, number of rows, and angles of elevation of the source and receiver.[9] Disturbances were also found to be influenced by seats outside the direct line of propagation. Cox and Davies discussed reflexion arrival time, using boundary-element and physical models to test attenuation reduction.[10] Seat dips were noted between 150 - 200 Hz; within the 100-300 Hz range described previously.[3, 6]

Lovetrie and Takahashi also modelled the effect, using ‘finite-difference time-domain’ methods and ‘locally reactive surface’ methods respectively.[7, 11] Lovetrie measured attenuation with centre frequencies of 80 Hz and 200 Hz, at varying receiver heights.[7] As can be seen in Figure 4, below, there is also evidence for a downward frequency shift with increasing height, similar to that found by Schultz and Watters.[2]

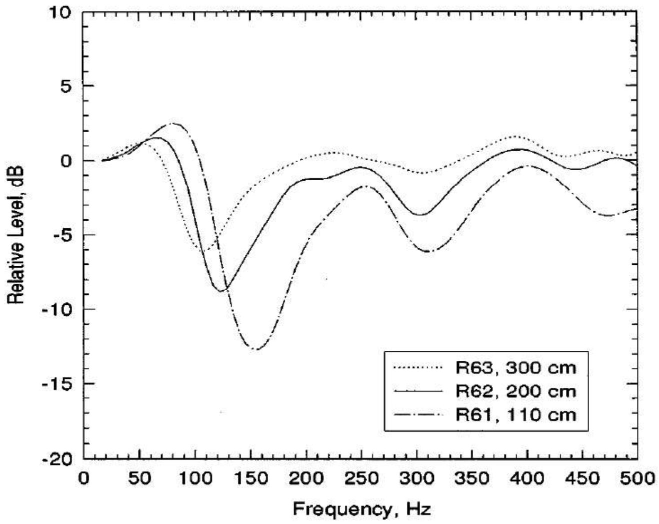


Figure 4 – Seat dip variance with height, constant 250 cm source height (from [7])

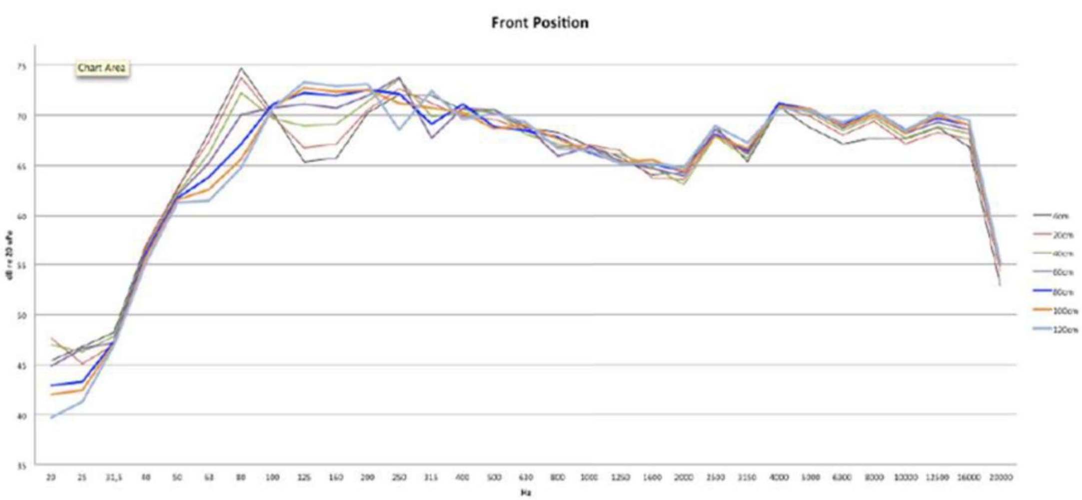
The seat dip has been shown to affect sound quality, at least under certain circumstances. Sessler and West claimed early sound degradation due to seat dips would reduce ‘envelopment’.[3] This has been considered a desirable characteristic for the performance of acoustic music.[12] However, Schultz and Watters suggested that sufficient late reverberation could compensate.[2] Others have suggested that the attenuation in the direct field could be compensated for by later reflexions .[4, 13] Toole has suggested that extended LF response may be why we prefer longer reverberation times at low frequencies.[14, (after 15)]

Cox and Davies found that 50% of listeners detected direct sound attenuation of greater than 5.9 dB at 200 Hz.[10] For early energy from 0 to 80 ms, an attenuation threshold of 3.8 dB would be required.[10, 14] In fact, the energy in this band is often used to calculate musical clarity.[10] Cox and Davies confirmed the results discussed in the previous paragraph, stating that differences in the reverberant field do not significantly affect attenuation perception below this threshold, and that seat-dip is subjective.[10] Additionally, the LF content may not be crucial ‘[for] subjective appreciation’.[2]

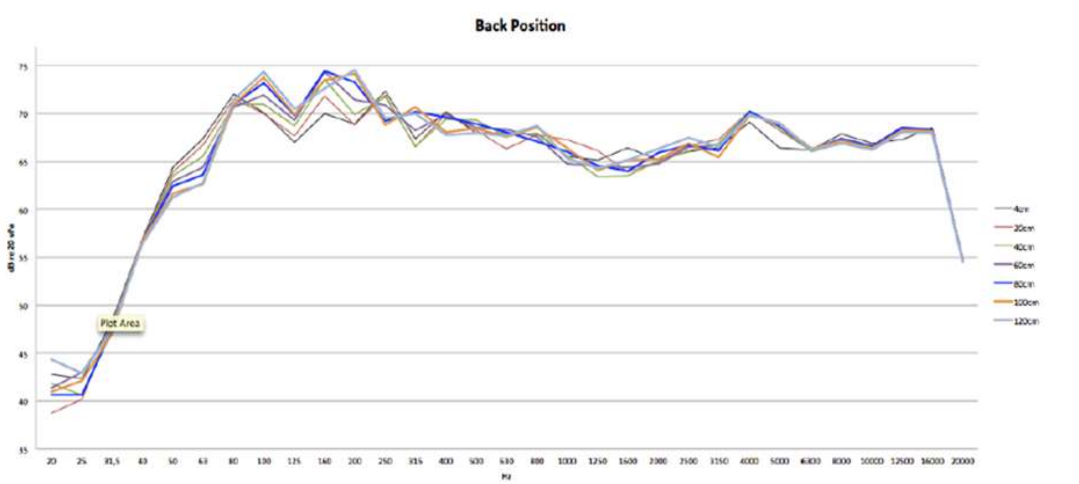
Tahvanainen *et al* determined that a lack of LF is recognized when the seat dip also affects the reverberant sound field.[5] A simulation of the seat dip effect followed, replicating ‘neutral’ sound fields from various concert halls.[13] Listeners were played ‘free-field’ and filtered stimuli. ‘Free-field’ stimuli were preferred, followed by the narrower filter. In ‘shoebox’ (rectangular) concert halls, listeners had greater difficulty noticing any seat-dip, supporting Barron’s experiments in fan-shaped halls.[4] Conclusions were that the seat-dip perception could be reduced by shoebox designs, and designing for sufficient early reflections was sufficient (as theorised by Schultz and Watters [2]).

To reduce disturbances, Sessler and West suggested steeply raking floors with a minimum angle of incidence of 15°, whereas Schultz and Watters suggest 30°.[2, 3] Bradley is in agreement with rakes greater than 15°.[6] However, Holman found seat-dip still affected cinemas with raked ‘stadium’ seating, despite a steep angle of incidence.[14] Toole also stated that the absence of reflections in cinemas would compound this issue, and, in addition, that even if we increase seat rake to avoid ‘near grazing incidence’, this may not reduce seat dip.[14] Bradley determined that lower ceilings reduce attenuation, and increase dip frequency by introducing additional reflected sound.[6] However, reflective ceilings may introduce unwanted colouration, reducing envelopment.[10]

Newell *et al* investigated measurement-microphone heights to achieve the most 'realistically-perceived sound quality'.[1] It was found that frequency responses measured at different calibration seats were similar above 500 Hz when microphone heights varied between 20 to 120 cm above the seat-backs. A closer measurement, at 4 cm, was significantly disturbed. By contrast, below 500 Hz, the responses differed considerably. Between 100 and 200 Hz, greater attenuation was noted closer to the seats, but there were also frequencies where the attenuation was reduced (or a reflective-boundary boost occurred): this 'augmentation' increased moving closer to the seats. Closer to the front of the seating area, the effect occurred with greater magnitude, possibly due to the steeper angle of incidence of the sound arriving from the loudspeaker.[1] Graphs of these measurements are reproduced in Figure 5.



a) Measurement towards front of seating area (from [1])



b) Measurement towards rear of seating area (from [1])

Figure 5 - Results from Newell's experiments

The subjective experiment in Newell's investigation concluded that perceived reverberance and low-frequency response increased further above the seating, but little else changed. Thus, it would appear that the height above the seats affects the objective (measured) room response more significantly than subjective perception.

3 CONCLUSIONS FROM LITERATURE SEARCH

Numerous studies over the past 50 years have clearly demonstrated that the rows of seats in concert halls and cinemas do, indeed, introduce significant changes in both the subjective and objective characters of the low-frequency sound; at least in the proximity of the seats for the sounds arriving from a forward direction. In the case of concert halls, the principal questions have been whether the effect was detrimental to the enjoyment of the music, and, if so, if anything could be designed differently so as to reduce the effect (such as introducing compensating reflexions). Obviously, in concerts of acoustic music, nothing can be done to change the instruments which are the sources of the sound.

By contrast, in cinemas, the sources of the sound are loudspeakers, which are usually mounted relatively higher than the instruments on a concert platform and are usually fewer in number than orchestral sources. What is more, cinemas generally have much lower reverberation (decay) times than concert halls, and have a greater range of seating rakes. The options to use acoustic means to 'smooth over' the seat dips tend not to be available in rooms of lower decay time, so the tendency has been to employ equalisation to the loudspeaker systems to try to compensate for the response disturbances given rise to by the seats. However, to what degrees this practice is either desirable or effective has been a moot point.

4 MOTIVATION FOR THE STUDY

In depth research into the specific effects of cinema seating on loudspeaker system calibration has long been required. The 'common sense' approach has led to the calibration microphones being placed at approximately the same height as the ears of a typical audience, or thereabouts, then equalising of the loudspeaker response to compensate for the seat dips by using a one-third-octave spectrum analyser and equaliser. Unfortunately, this 'intuitively obvious' approach has many flaws. What is more, since cinemas are businesses, time and budget constraints have also led to the practice of carrying out calibrations using microphones clipped to seats, and cinema operators are tending towards the automatic calibration of cinema loudspeaker systems, often with scant regard for the appropriateness of the microphone positioning. Whilst this seems to be unadvisable, little evidence has been published to conclusively prove the folly of the technique.

Existing standards (such as SMPTE202:2010) require the microphone to be placed within relatively close proximity to the seats,[16] but human auditory systems are not the same as microphones. Ears and brains use localisation methods including inter-aural time difference (ITD) and inter-aural level difference (ILD) to distinguish direct sound from early reflexions. Since a microphone only measures pressure fluctuations, and sums the direct and reverberant components, current calibration methods are essentially 'time-blind', because there is no differentiation between the different sounds arriving at different times. Thus, calibrating pressure responses using 1/3rd-octave-band equalisation, which cannot work equally well for all listeners, may not achieve good subjective sound quality since a subjectively 'good' unequalised sound may be coloured by any equalisation applied in an attempt to 'correct' the 'time-blind' response as measured via any microphone(s) at ear height.

Also, SMPTE 202 simply states that sound arriving at '*near grazing incidence to the seats'* causes a seat-dip between approximately 80 - 125 Hz, which is more significant with shallower rakes.[16] However, it has been shown in Section 2, above, that disturbances due to rows of seating can occur well above this range.

Averaging across microphone positions near seating which is known to disturb the sound field, and then making generalised corrections to the direct sound (which is known to arrive intact) is likely to degrade the perceived sound quality for the majority of the audience. Also, making corrections to the direct sound-field cannot correct issues in the reverberant field. A true 'null' in the frequency response is not correctable using equalisation.[17] A cancellation is a cancellation: more energy in the band means more energy for the cancellation.

It has been proposed by numerous prior investigators that, as we are unlikely to get rid of seat-dip effect, we should calibrate cinemas using a higher microphone placement. However, there have been few subjective tests comparing sound fields whose responses had been calibrated at different heights. It would seem obvious that if a listener prefers the sound field in a less 'acoustically-disturbed' location, it makes no sense to calibrate close to the seat if it will lead to unnecessary and inappropriate equalisation without actually improving the perceived sound.[1] There has been little experimentation carried out to compare the objective and subjective differences, and it is clear that better-standardised 'perceived' frequency responses are necessary for reliable representation of programme material in every cinema.

5 COMPARISON OF OBJECTIVE AND SUBJECTIVE TESTING

5.1 Description of venues

Three venues were tested: the Lanchester A lecture theatre and the Turner Sims concert hall, both at Southampton University, and the Sonar cinema at Southampton Solent University. All the seats were upholstered with 5 cm to 7 cm deep padding.

Lanchester A, shown in Figure 6, is a 227-seat, fan-shaped venue, being 15.5 metres from the screen to the back wall, and 14.1 metres at its widest, but tapering to 7 metres at the screen. The room is carpeted, and has 75 cm desks in front of most seats. The floor is stepped, with successive rows increasing by 15 cm (a shallow rake angle). The ceiling is lower than that of the other venues (2.8 m) and slopes with the seating. Each seat back is 91 cm high (the lowest of the three venues).

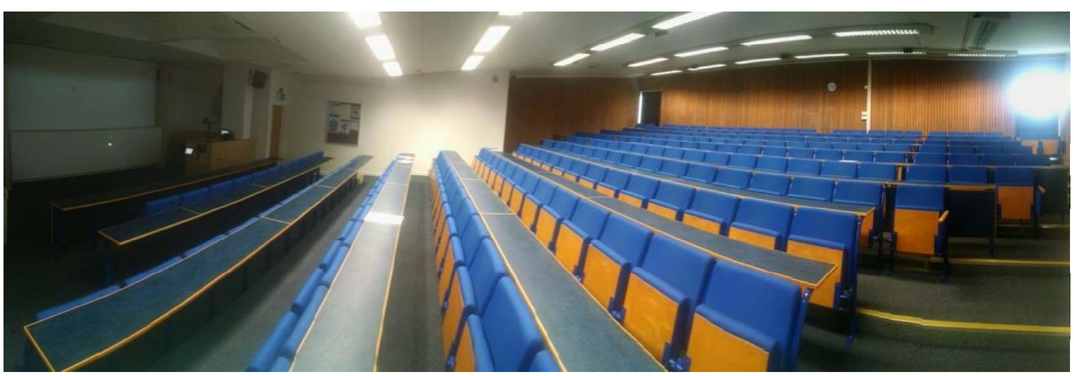


Figure 6 - Photo of Lanchester A

The Turner Sims Concert Hall has a 372-seat capacity. It is 17.1 metres wide by 25 metres long, with a 9.1-metre-high ceiling and 99 cm seat-back height. The 'shoebox' design means that the ceiling does not slope with the seats, which are moderately raked with a 20 cm step-height. This venue has a highly reflective parquet floor, and the walls are of brick with diffusers on the parallel wall surfaces. The result is a rather high reverberation/decay time, which is atypical of modern cinemas but not so of older venues. The hall is shown in Figure 7.

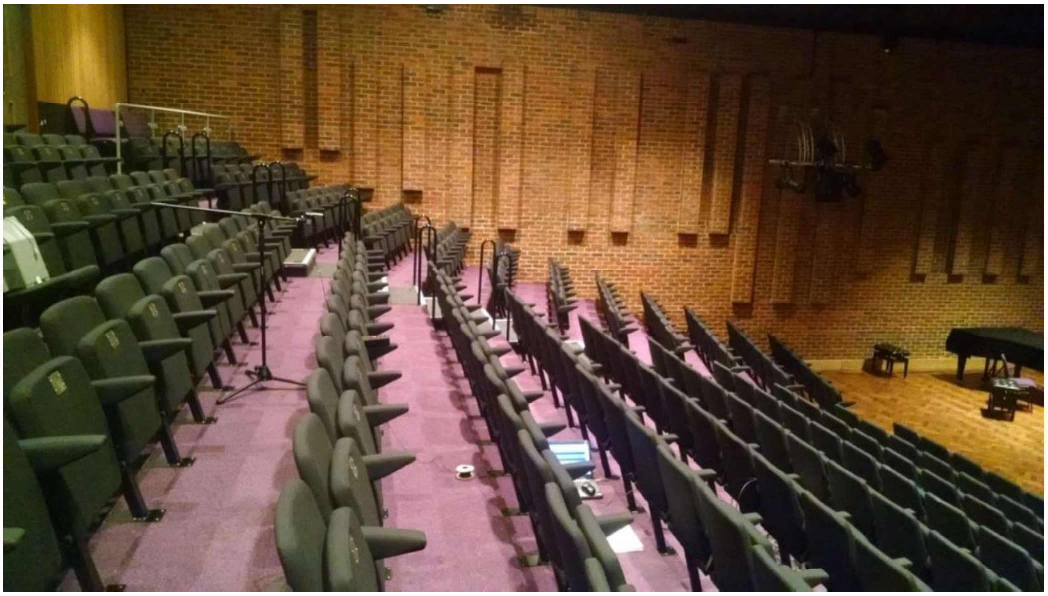


Figure 7 - Photo of Turner Sims

The Sonar cinema, shown in Figure 8, has a 96-seat capacity and is of a rectangular plan, 11.4 m wide and 9.4 metres long, with 101 cm-tall, steeply-raked seats (25 cm step height). It is certified for Dolby Atmos cinema screenings and doubles as a lecture theatre. This room is fitted with sound-absorption panels to decrease its reverberation time, for good intelligibility both during films and lectures. It is worth remembering that with multi-channel film formats, the ambience and spaciousness are to be delivered by the soundtrack itself. No 'help' is required in the way that would be expected from a concert hall, so the low decay time in this room is now quite typical.

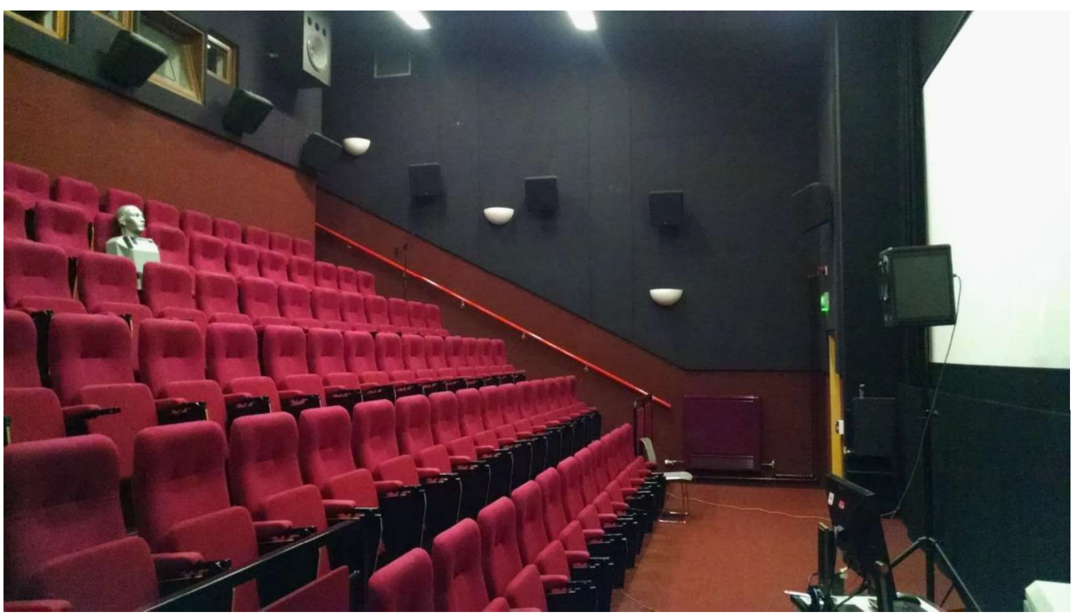


Figure 8 - Photo of Sonar cinema

5.2 Measurement procedure

Measurements were made at the standard 'calibration' seat for cinemas, 2/3rds of the way back in the room'. [16] The test loudspeaker (Tannoy CPA 12, a dual-concentric type) was set up centrally, as close as possible to the front wall (to simulate the sound field from the centre loudspeaker located behind the screen), with the stand-height adjusted to ensure the measurements were not affected by any poor coverage resulting from measuring outside the directivity range of the loudspeaker. Two different loudspeaker heights were used. In Lanchester A, the lower ceiling required the loudspeaker to be placed suitably far from the ceiling to avoid excessive disturbance from reflexions. The centre of the loudspeaker driver was located 220 cm from the floor (the highest practicable height with the equipment used). This steeper angle better represented that from typical cinema-screen loudspeakers, as opposed to the loudspeaker heights often used to make the measurements of concert halls discussed in the literary review.

After the venue and seat dimensions had been duly noted, the measurement microphone was set up above the back of the test seat. The 85 dBC specified by SMPTE RP-200 was achieved without clipping,[18] and pink noise playback was recorded at each height, using the measurement microphone. (This level is recommended in order to be well-clear of either the noise floor or the overload levels.) A calibrated B&K 4954 free-field measurement microphone was used, with a flat frequency-response at 0° incidence. The programme material for the subjective tests was a monaural soundtrack sample, representative of typical output from the centre/front loudspeaker.[1] This was played back over the loudspeaker and recorded binaurally using a dummy head. The setup is shown in Figure 9.

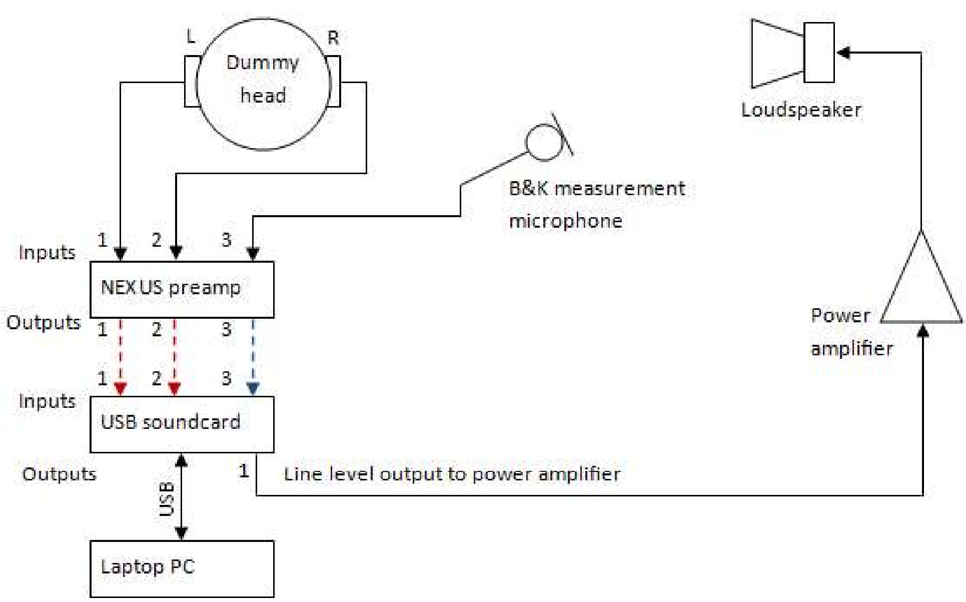


Figure 9 – Test equipment setup

5.3 Subjective experiments

Subjective experiments involved reproduction of the recorded binaural sound fields. Sennheiser HD 203 closed-back headphones were used for playback to allow adequate isolation from external noise in the test environment, with this particular model having a good low-frequency response.

Since recorded disturbances scale linearly with level, it was deemed unnecessary for headphones to reproduce SPLs identical to those incident on the dummy head[1].

5.3.1 A/B/X comparison of recordings in same venue, different heights

This test aimed to determine whether listeners could reliably differentiate between sound fields recorded at different heights. If this was possible, it would suggest that disturbances due to the seating and room geometry change with height, and that this difference is above the perception threshold.

To assess this objective, two-alternative forced choice A/B/X tests were used, where listeners chose which of A and B sounded most like X. [19] 'Forced' refers to subjects having to choose one option to continue, even if they cannot detect a difference. The test was also 'double-blind' as neither the listeners nor researchers knew which sample corresponded to A or B (this was assigned by the test software). A two-tailed binomial hypothesis test was used to determine listeners' ability to reliably differentiate between A and B[20, 21, 22, 23].

A and B were assigned to dummy head recordings made at different heights as shown in the table below, to determine whether listeners could identify a difference between recordings at different heights. Low recordings were made between 1.0 and 1.2 m from the floor, and at least 15 cm from the seat (as recommended in SMPTE 202:2010[16]), but the precise height varied due to differences in seat height (see Table 1). High recordings (theoretically less acoustically-disturbed) were made as far as possible from the seat back in each venue. For statistical significance, each A/B/X test was repeated until 10 trials per venue per listener were completed.

Test number	'Which is X?'	
1	Lanchester A, 120 cm	Lanchester A, 160 cm
2	Turner Sims, 120 cm	Turner Sims, 160 cm
3	Sonar, 112 cm	Sonar, 140 cm

Table 1 - Microphone heights in the different venues

5.3.2 A/B comparison of recordings in same venue, different heights

This test aimed to determine whether listeners preferred a 'standard-calibrated' room response versus an 'incorrectly-calibrated' one. This was determined using a simple A/B test. If listeners preferred the 'standard-calibrated' sound-field, calibration methods in use must go some way towards 'correcting' for the disturbances.

A series of equalization response-corrections were calculated for each venue and each height by subtracting the 1/3rd octave band levels (with pink noise used as an input) from the required X-curve specified in SMPTE 202:2010[16]. These response-corrections could then be applied to the binaural recordings made at each height in order to 'correct' them to the X-curve response. For example, applying the 120 cm response-correction to a binaural recording made at 120 cm would result in a binaural recording that mimics that which would be heard in a 'standard-calibrated' venue (i.e. we have successfully calibrated the venue according to SMPTE standards). On the other hand, applying the 160 cm response-correction to a binaural recording made at 120 cm would simulate a recording made in an incorrectly-calibrated venue.

Four sets of comparisons were therefore made: low height plus low correction was compared with high height plus low correction, and low height plus high correction was compared with high height plus high correction. The test heights are shown in Table 2.

Venue	Lanchester A		Turner Sims		Sonar	
'Low' dummy head recording height (cm)	120		120		112	
'High' dummy head recording height (cm)	160		160		140	
Corrected to (cm)	120	160	120	160	112	140
Trial	4	5	6	7	8	9

Table 2 – test heights for the second trial

Current standards presume that recordings made at both 120 cm and 160 cm can be calibrated to sound identical. If listeners prefer samples equalised by measurement at the *standard* height they would consistently select *'low'* samples with 'lower height' response-corrections applied (or 'high' samples with 'high' response-corrections), and we could conclude that the equalisation was effectively able to 'correct' for the disturbances resulting from seating and geometry. Conversely, if listeners did not consistently select correctly-equalized recordings, we would not have been successful in influencing listener choices by calibrating using the method in current standards, and they would *not* have been shown to prefer the frequency-response over that which was incorrectly calibrated.

6 OBJECTIVE AND SUBJECTIVE TEST RESULTS AND DISCUSSION

6.1 Objective results

6.1.1 Lanchester A

The results from the first venue are shown in Figure 10. These differed significantly from initial 'trial runs' completed earlier in the project, when a slightly different loudspeaker location was used. We would not expect such extreme variability when measuring the same seat because the measurements were still within the loudspeaker directivity range, so this suggests that the seat-dip behaviour is sensitive to source position.

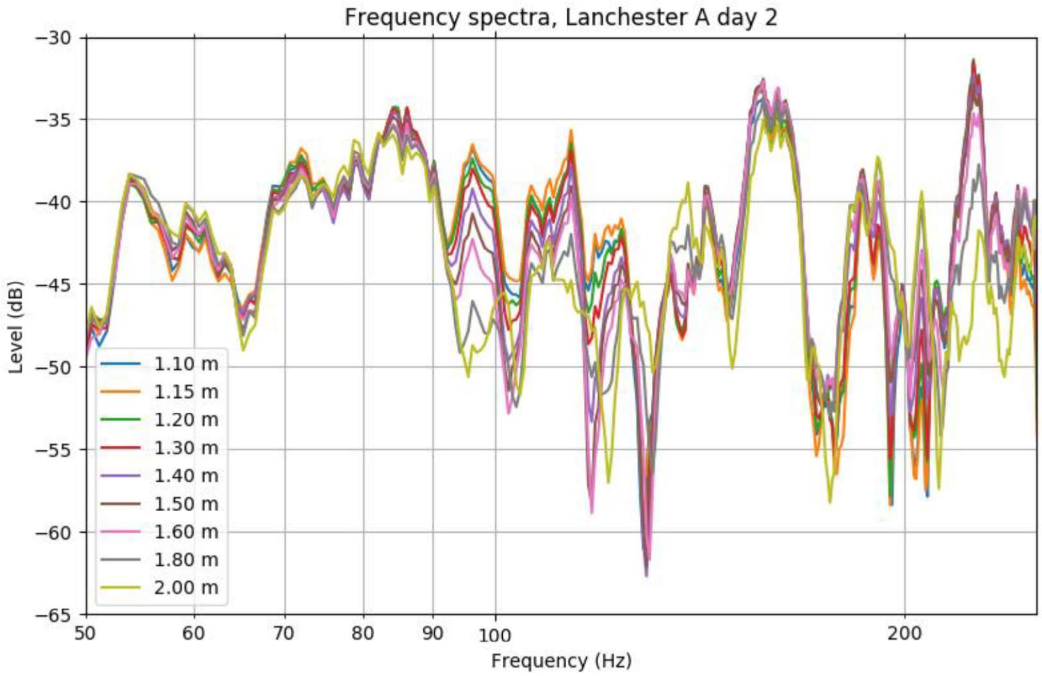


Figure 10: Frequency spectra from Lanchester A

Seat dips were found to be within the range measured by Lovetrie, with attenuation varying between 10 and 20 dB. It would appear that measuring by means of multiple microphone positions near the test seat and performing the spatial averaging specified in SMPTE 202[16] would be essential in order to attempt calibration, but these results do not inspire confidence that any correction based on time-averaged responses, especially in third-octave bands, would be a suitable calibration method.

6.1.2 Turner Sims

The Turner Sims concert hall is a highly reflective ‘shoebox’ design; additional interference between modes results in many more maxima and minima in the frequency spectra. It would appear from the results shown in Figure 11 that at nearly every peak and trough there are variations with measurement height in the amount of attenuation.

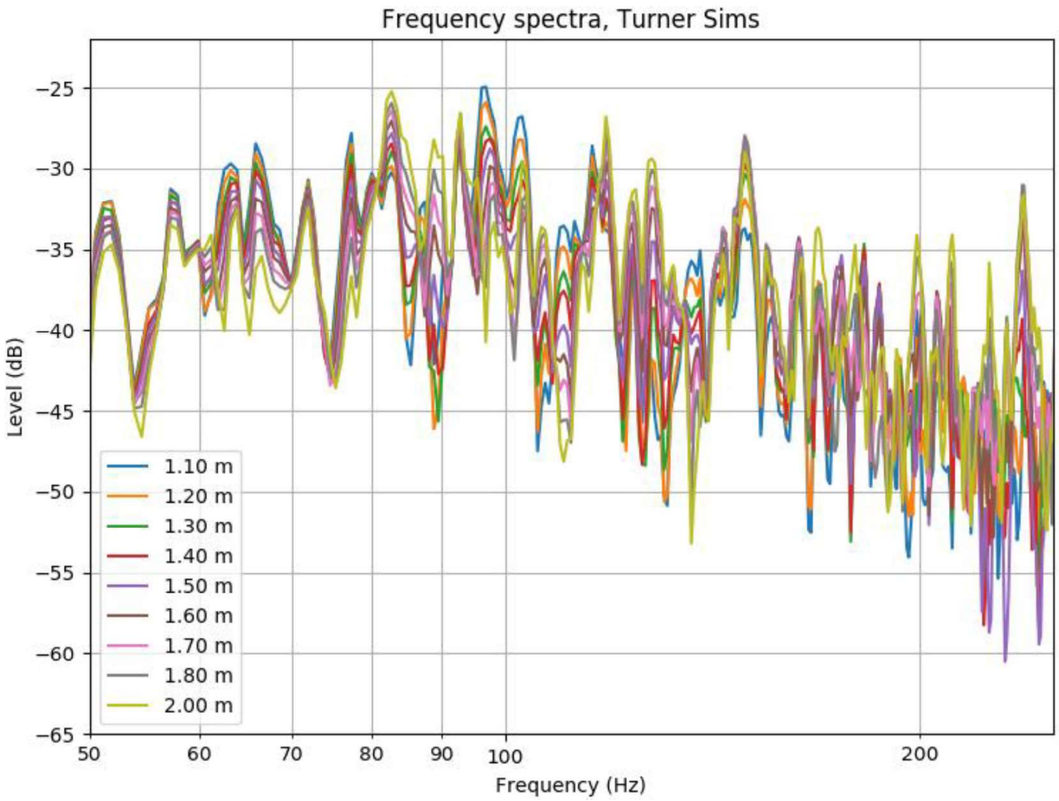


Figure 11: Frequency spectra from Turner Sims

Up to 67 Hz, measurements at different heights correlate reasonably well, varying by about ±3 dB. Interestingly, above 73 Hz, it would appear that frequency response peaks move to slightly higher centre frequencies with increasing height, and frequency response dips move to lower centre frequencies with height (as found by Schultz and Watters[2]).

A possible seat-dip was found at 84 Hz, where attenuation reduces with increasing height. This dip is wide, ranging up to 95 Hz. Strangely, the centre dip-frequency is lower than that measured in Lanchester A, despite increased floor rake (noted to increase the dip-frequency.[3] A notable cross-over point occurred at 110 Hz, where the dips in the frequency response occurred in the spectra recorded between 1.1 and 1.4 metres, although the dips between 1.5 metres and 2.0 metres occurred at higher frequencies. This suggested that the dip centre-frequency increases with increased measurement height, although the amount of attenuation within the dip region remained constant. Again, it is difficult to state whether this disturbance was due to the seats, or not.

Beyond 170 Hz, higher measurement heights resulted in less disturbed spectra with levels that were consistently higher (by 5 to 10 dB) than those measured at lower heights. This could point towards a ‘wide’ seat-dip which resulted in increased level for higher microphone heights across a far wider frequency range than measured in the other venues.

The longer reverberation time of the Turner Sims hall resulted in increased modal overlap when compared to the other venues, meaning that the frequency response was very disturbed. The highly reflective floor may also, to some degree, have introduced a ‘floor dip’.

6.1.3 Sonar cinema

In the Sonar cinema, once again, below 70 Hz the responses conformed well. (The increased response in the 50 - 70 Hz band closer to the seat could be attributed to a reflective-boundary boost.) Despite having steeply raked seats and the fewest number of rows of any other venue tested, the discrepancies from the flat response seem to be larger than the other venues, with a maximum difference of 23 dB. From Figure 12 it can be seen that the peaks at 74 Hz and 90 Hz have no height-dependence, and so may not be due to the seats. By contrast, within the 102 - 110 Hz band, the attenuation firstly increases and then decreases with height. This cross-over could be caused by overlapping modes.

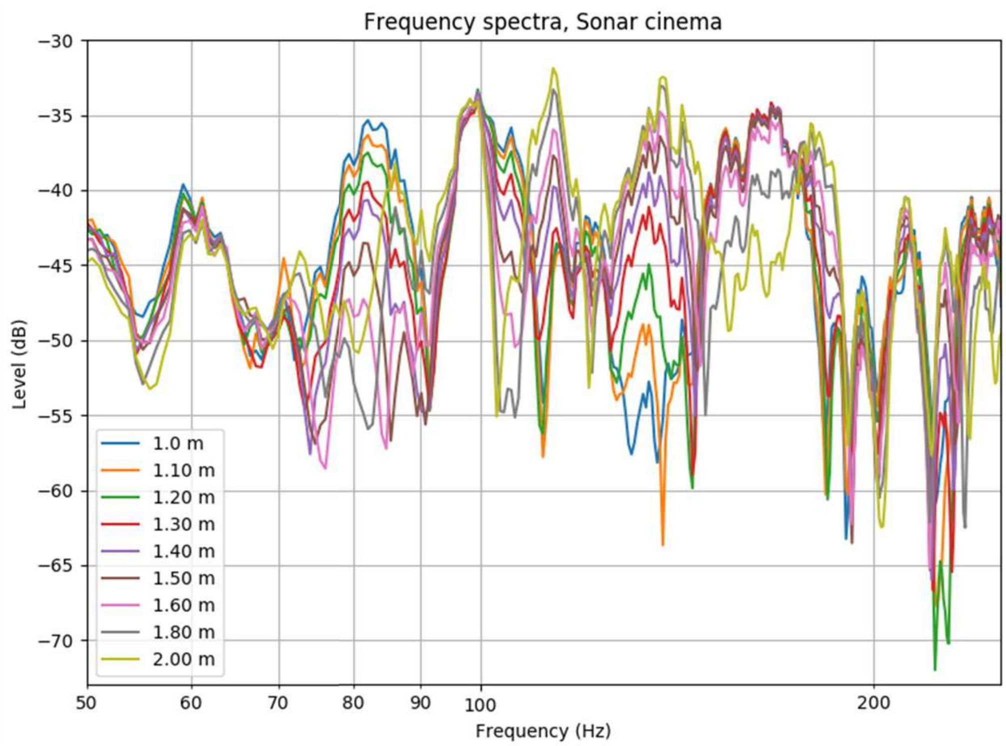


Figure 12 - Frequency spectra from Sonar cinema

A secondary seat-dip was identified, centred around 140 Hz, with a discrepancy of 23 dB between the lowest and highest dips. Here, the amount of attenuation increased closer to the seats, and the dip (or even boost frequency beyond around 1.4 m) slightly increased with measurement height. As we would expect, since this venue is the lowest-capacity and least reverberant of all venues measured, the number of 'cross-over' points, where the frequency vs height characteristics switch, is lowest. Above 200 Hz, the response is flatter and the spectra appear to be similar, despite being well above f_s, which could be due to the comparative lack of reflexions versus (for example) the Turner Sims theatre. It is clear from the full spectrum that it is the 80 - 200 Hz region which is most disturbed.

6.1.4 Summary of objective results

Analysis of the objective plots enabled seat-dips to be identified as 'troughs' (areas of decreasing attenuation for increasing microphone height). Results outside the 50 - 250 Hz range have a good degree of similarity, and do not vary significantly with height, suggesting that any response-variation outside this frequency range was not due to the seating. Interestingly, however, increased seat-back height did not always lower the dip-frequency. It was also difficult to determine seat-dip centre-frequencies in the venue with the higher decay-time (Turner Sims). Reflective-boundary boosts also occurred in Lanchester A, likely due to the desk and ceiling reflexions.

Observed disturbances below the seat-dip frequencies are likely to result from alternating constructive and destructive interference from room modes and reflexions causing comb-filtering. 'Cross-over' points similar to those found by Newell *et al*[1] and Gedemer[24] are present on the normalized plots: an example of which is shown in Figure 13. It can be seen that there are bands where the level decreases and increases with height; bands with decreasing attenuation with increased height are attributed to the seats.

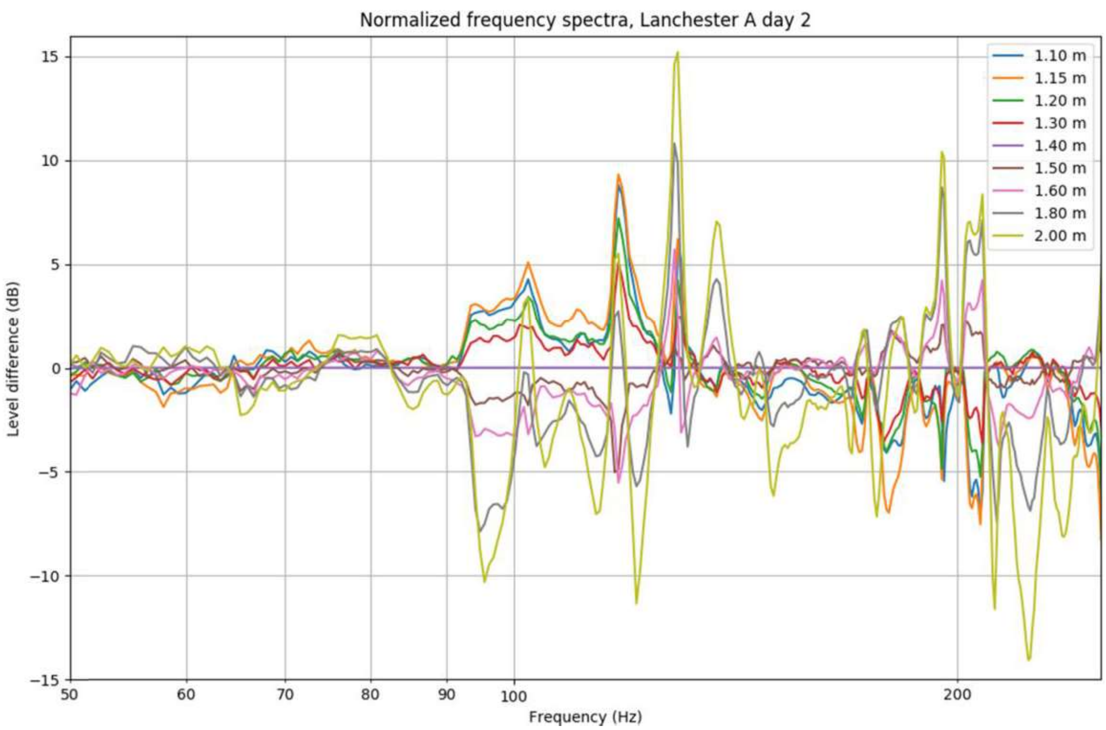


Figure 13 - Example of frequency-response plot 'normalized' against the 1.4 m frequency response, showing cross-over points.

Severe variability between results was encountered when slightly changing the loudspeaker and/or microphone positions, so some averaging would be necessary when calibrating, although it must be recognised that this is a *real* variation with position. Averaging is only to find a calibration mean.

Curiously, it was noticed that increased rake and decreased number of rows both appeared to result in a greater seat-dip attenuation, whilst conventional thinking would suggest that the opposite is likely to be true.[9] However, Newell *et al* did find that the 'degree of differences between 40 and 200 Hz' was much greater closer to the front of the venue, where the angle of incidence to the seating was steeper.[1]

The tests being reported here did show the seating to have significant, highly-variable effects on the measured response of the three venues tested. The seat-dip appears to interact with the other reflected energy in the rooms; which makes it difficult to isolate. However, strong ceiling reflections and scattering seem to reduce the resulting attenuation, as concluded by Barron and Bradley.[4, 6] As found by Holman, stadium seating was not found to reduce the seat-dip effect.[14] This is interesting as some of the literature reviewed in this paper has suggested the opposite to be true.[2, 3, 9]

6.2 Subjective tests

6.2.1 A/B/X comparison of recordings in same venue, different heights

The first of the subjective tests aimed to determine whether listeners could reliably identify differences between sound fields at different heights by comparing 'disturbed' recordings close to the seat and 'undisturbed' recordings further from it.

Based on a binomial statistical test, the null hypothesis was either rejected or maintained. Results are shown in Table 3, and a further description is given in Section 5.3.

	/times X identified of 10 attempts			Lanchester A		Turner Sims		Sonar	
Subject	Lanchester A	Turner Sims	Sonar	$P(X = x)$	Reject H_0?	$P(X = x)$	Reject H_0?	$P(X = x)$	Reject H_0?
1	10	7	9	0.001	Yes	0.117	No	0.010	Yes
2	9	10	9	0.010	Yes	0.001	Yes	0.010	Yes
3	5	8	3	0.246	No	0.044	Yes	0.117	No
4	8	7	6	0.044	Yes	0.117	No	0.205	No
5	7	6	7	0.117	No	0.205	No	0.117	No
6	8	6	8	0.044	Yes	0.205	No	0.044	Yes
7	8	5	7	0.044	Yes	0.246	No	0.117	No
8	5	6	5	0.246	No	0.205	No	0.246	No
9	7	6	6	0.117	No	0.205	No	0.205	No
10	10	7	6	0.001	Yes	0.117	No	0.205	No
Total observed	77	68	66	1.96×10^{-8}	**Yes**	1.13×10^{-4}	**Yes**	4.58×10^{-4}	**Yes**
Total n	100	100	100						

Table 3 - Statistical results based on the binomial test. The first three columns indicate the number of times listeners correctly identified X for each venue

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Results showed that 6 of 10 listeners could reliably identify X in the Lanchester A recordings, with just 2 listeners able to reliably identify X in the Turner Sims concert hall, increasing to 3 for the Sonar cinema. However, when considering the group's performance across all three venues, the total effect was that the null hypothesis could be rejected: in general, listeners *could* reliably differentiate between sound fields at different heights. Therefore, listeners *are* affected by the sound field disturbances due to the seats, since they can perceive a difference when measuring at different heights above them.

Some listeners noted that dialogue remained identical between the two samples, and that the difference was easier to identify using the musical part of the samples. The music contained a broader range of frequency content compared to dialogue, making discrepancies easier to identify.

6.2.2 A/B preference test – recordings 'correctly' and 'incorrectly' calibrated

The second set of tests aimed to determine whether equalisation to the target response in 1/3rd octave band corrections was suitable for correcting the discrepancies in the sound field. Listener selection of 'low' samples with 'low' corrections applied, or 'high' samples with 'high' corrections applied, would suggest that current calibrations are sufficient. If listeners picked the 'low' sample with 'high' equalization, for example, it would be possible to conclude that the calibration method used (mimicking current SMPTE/Dolby recommendations) was insufficient. Some of the results are shown in Table 4.

Subject	Lanchester A, corrected to 120 cm	Lanchester A, corrected to 160 cm	Turner Sims, corrected to 120 cm	Turner Sims, corrected to 160 cm	Sonar, corrected to 112 cm	Sonar, corrected to 140 cm
1	120	120	160	120	140	112
2	160	160	160	160	140	140
3	160	120	160	160	140	140
4	160	120	120	120	112	140
5	120	160	160	160	140	112
6	120	160	160	120	112	112
7	120	120	160	160	140	140
8	160	160	120	160	140	112
9	120	160	160	120	140	112
10	120	120	120	120	112	140
Expected preference	120	160	120	160	112	140
No. of subjects with this expected preference	6	5	3	5	3	5

Table 4 - Results of the preference test

The results showed that the equalisation method used was *not* suitable to correct the sound-field disturbances in the venues tested, since there was no evidence to suggest that listeners preferred the room when its response was equalized to the target response using corrections corresponding to the recording height, versus a room that was not equalised to the same target. Despite the applied equalisation corrections differing significantly, many listeners commented that it was difficult to select any one of them as having 'improved' sound quality.

Thus, the results of the tests have disproved the idea that calibration to the target response using 1/3rd octave band corrections (as specified in current standards) is a generally suitable method for correcting disturbances; and this is likely to extend to other venues. Corrections resulting from the application of the method in current standards did not result in a sound field that listeners preferred. As stated by Toole,[25] there are serious doubts that we can correct seat dip disturbances using equalisation. Newell *et al* recommend that floor and seat dips must *not* be equalised.[26]

7 CONCLUSIONS

Objective tests at a range of heights in three theatres found that sound fields were significantly disturbed close to the seats, with the seating affecting all results measured. Seat dips were principally identified by the fact that their associated attenuation decreased with increased measurement height.

Subjective tests determined that listeners could reliably differentiate between sound fields recorded at different heights. This being the case, and as the microphone height cannot remove the presence of a seat dip for a seated person, it gives weight to the proposals that loudspeaker-calibration, if carried out in the seating area, should take place with the microphone(s) some distance above the seats. Equalising the dip will inevitably lead to a loss of headroom and the colouration of the direct sound for the whole audience, which is pointless if it does not result in a sound that is preferable for any people for whom it is supposed to be beneficial.

Unfortunately, when looking at the seat dips in cinema theatres, several other response disturbances may also be present which are unlikely to be correctable by equalising the direct sound: for example, interference due to reflexions from the walls and ceiling. When equalising room responses to the target response from measurements made close to the seats, listeners showed *no preference* between recordings with the standard response-corrections applied or recordings calibrated at the 'incorrect' height. This points towards the fact that these response irregularities are impossible to equalise by compliance with any standard calibration procedure. However, strong ceiling reflections and general scattering do seem to reduce the resulting attenuation. Consequently, using time-averaged pink noise measurements to determine which discrepancies in the frequency responses specifically result from the seating is very difficult. As found by Holman, the stadium seating in this investigation was not found to reduce the seat-dip effect, although the lack of strong reflections in the Sonar cinema may have highlighted the issue.[14]

A further result of this complexity is that the overall response will be significantly different for every seat in the house, making overall correction even less feasible. Since listeners did not prefer audio samples calibrated using the suggested methods, the current guidelines for the 'correction' of the seat dips is clearly not effective in practice. Seat dips, it would appear, are best left to the human auditory system to deal with as there is no electroacoustic fix.

In conclusion, this investigation explored the effects of rows of seats on measured sound-fields by performing tests within three venues. Calibrating a cinema theatre based on current standards, by equalising the direct sound field from loudspeakers using sound-field measurements made close to seating, was determined to be inadvisable. 'Time-blind' analysis and calibration techniques are likely to be inadequate except when correcting the direct sound response of a loudspeaker[25], and corrections to the direct sound field are unlikely to improve response discrepancies resulting from seat-dips.[25, 26]

If a time-blind calibration method is to be used, it would seem to be more appropriate for the microphones to be placed further from the floor, where the sound-field disturbances due to the seats are less dominant. This technique would reduce the headroom limitations and the colouration of the direct sound which can result from the seemingly futile attempts to equalise the attenuation in the region of the seat dips. It begs the question: why risk colouration and overload-distortion if the result of the equalisation does not improve the perception of the sound for the audience?

8 REFERENCES

1. P. Newell, "The Relationship Between Subjective and Objective Differences at Different Heights Above Cinema Seating", Proceedings of the Institute of Acoustics, vol. 37, no. 4, 2015.
2. T. Schultz and B. Watters, "Propagation of Sound Across Audience Seating", The Journal of the Acoustical Society of America, vol. 36, no. 5, pp. 885-896, 1964.

3. G. Sessler and J. West, "Sound Transmission Over Theatre Seats", The Journal of the Acoustical Society of America, vol. 36, no. 9, pp. 1725-1732, 1964.
4. M. Barron, "The Effects of Early Reflections on Subjective Acoustical Quality in Concert Halls", PHD, University of Southampton, 1974.
5. H. Tahvanainen, J. Pätynen and T. Lokki, "Studies on the Perception of Bass in Four Concert Halls.", Psychomusicology: Music, Mind, and Brain, vol. 25, no. 3, pp. 294-305, 2015.
6. J. Bradley, "Some Further Investigations of the Seat Dip Effect", The Journal of the Acoustical Society of America, vol. 90, no. 1, pp. 324-333, 1991.
7. J. LoVetri, D. Mardare and G. Soulodre, "Modeling of the Seat Dip Effect Using the Finite-Difference Time-Domain Method", The Journal of the Acoustical Society of America, vol. 100, no. 4, pp. 2204-2212, 1996.
8. H. Tahvanainen, "Analysis of the Seat Dip Effect in an Opera House", 1st ed. Aalto University, 2016.
9. W. Davies and Y. Lam, "New Attributes of Seat Dip Attenuation", Applied Acoustics, vol. 41, no. 1, pp. 1-23, 1994.
10. W. Davies and T. Cox, "Reducing Seat Dip Attenuation", The Journal of the Acoustical Society of America, vol. 108, no. 5, pp. 2211-2218, 2000.
11. D. Takahashi, "Seat Dip Effect: The Phenomena and the Mechanism", The Journal of the Acoustical Society of America, vol. 102, no. 3, pp. 1326-1334, 1997.
12. M. Barron, "Bass Sound in Concert Auditoria", The Journal of the Acoustical Society of America, vol. 97, no. 2, pp. 1088-1098, 1995.
13. H. Tahvanainen, A. Haapaniemi and T. Lokki, "Perceptual Significance of Seat-Dip Effect Related Direct Sound Coloration in Concert Halls", The Journal of the Acoustical Society of America, vol. 141, no. 3, pp. 1560-1570, 2017.
14. F. Toole, '*Sound Reproduction*', 1st ed. Amsterdam: Elsevier, 2008, pp. p50, 124.
15. L. Beranek, '*Music, Acoustics and Architecture*', 1st ed. Huntington, New York: R.E. Krieger, 1962.
16. SMPTE document ST202:2010 – 'For Motion Pictures - Dubbing Stages (Mixing Rooms), Screening Rooms and Indoor Theaters -- B-Chain Electroacoustic Response'
17. G. Ballou, 'Handbook for Sound Engineers', 1st ed., pp. 189-90, Focal Press, Boston, USA, 2002.
18. "Relative and Absolute Sound Pressure Levels for Motion-Picture Multichannel Sound Systems; Applicable for Analog Photographic Film Audio, Digital Photographic Film Audio and D-Cinema", SMPTE, 2012.
19. Martin, 'Introduction to sound recording: Two-alternative Forced Choice', 2006.
20. L. Harris, 'Using Statistics to Analyse Listening Test Data: Some Sources and Advice for Non-Statisticians', Proceedings of the Institute of Acoustics, Vol. 31, no. 4, 2009.
21. R. Wolfe and D. Firth, "Modelling subjective use of an ordinal response scale in a many period crossover experiment", Journal of the Royal Statistical Society: Series C (Applied Statistics), vol. 51, no. 2, pp. 245-255, 2002.
22. B. Fazenda, How to Design and Conduct Listening Tests for Audio and Acoustics, 1st ed. 2015.
23. E. McCormick and J. Bachus, "Paired comparison ratings. I. The effect of ratings of reductions in the number of pairs.", Journal of Applied Psychology, vol. 36, no. 2, pp. 123-127, 1952.
24. L. Gedemer, 'Predicting the In-Room Response of Cinemas from Anechoic Loudspeaker Data', AES 57th International Conference, Hollywood, CA, USA, March 6–8, 2015.
25. F. Toole, "The Measurement and Calibration of Sound Reproducing Systems", Journal of the Audio Engineering Society, 2015.
26. P. Newell, "A New Draft Proposal for the Calibration of Sound in Cinema Rooms (21/4/12)", AES, 2012.

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