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by Mike Barron

ABSTRACT

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See also:

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Taking account of loudness constancy for the loudness criterion for concert halls

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Abstract

One of the surprises from analysis of results of an objective and subjective study of British concert halls (1988 Acustica 66, 1–14) was that the subjective judgement of loudness in concert halls is influenced not only by sound level but also by the source–receiver distance. This response implies that the same sound level is judged louder at positions further from the orchestra platform. Whereas level decreases with dis-tance in actual halls, loudness is judged more-or-less independent of position in average halls (except at positions close to the platform and seats overhung by balconies). As an observation it ties in with evi-dence from experimental psychologists for loudness constancy throughout a space. The sound strength G is the sound level in an auditorium normalised to the sound power level of the source; the traditional criterion of acceptability for level is that G > 0 dB. The paper proposes that, on the basis of subjective evi-dence and objective behaviour in auditoria, the criterion for G should not be a unique value of G but rather a function of source–receiver distance.

1. Introduction

It is generally acknowledged that sufficient loudness is an important component of the best concert hall acoustics and that sound level is a major determinant of this subjective effect. The sound level, as determined by the hall design, is measured as the strength (G dB), now specified in ISO3382 [1]. A lower limit for adequate loudness has been proposed as $G \geqslant 0$ dB. The proposal presented here is that the lower limit should also be a function of source–receiver distance.

The lower limit was put forward in Refs. [2,3] based on experience gained in the author's objective and subjective survey of British concert halls. Previously Lehmann and Wilkens [4], based on their survey of six German concert halls, had proposed a minimum criterion of $G = +3$ dB. This seems excessively severe as it implies that 30% of their chosen seat positions were too quiet. For the British survey, this criterion places 60% of measured positions with inadequate loudness! Evidence gained from the subjective survey of the British halls suggested a criterion for the minimum of 0 dB as acceptable for the total sound level. Ideally this figure of 0 dB refers to the average over the octaves 125–2000 Hz. This limit does not appear to have been challenged in the intervening years.

To make the case for the change of criterion, it is necessary to discuss behaviour, as a function of source–receiver distance, of both sound level in halls and subjective loudness. The following discussion uses two frequency ranges: mid-frequency, which is the mean of three octaves 500 Hz, 1000 Hz and 2000 Hz, and full-frequency, which is the mean of five octaves 125–2000 Hz.

The objective situation will be dealt with first, followed by the subjective leading to the relation between the two. The subjective evidence comes first from a study by the author, which is followed by consideration of work from experimental psychologists. An earlier version of this paper was presented at the International Congress on Acoustics in Madrid in 2007 [5].

2. Sound level behaviour in concert halls

The traditional theory for sound level in rooms containing an omni-directional point source is that two components are considered: the direct and reflected sound. The direct sound is taken to behave according to the inverse square law, while traditionally the reflected component was taken to be constant throughout the space. Barron and Lee [6] and Barron [2] presented a revised theory for sound level, which proposed that the reflected component decreases as source–receiver distance increases, Fig. 1. The rationale behind the proposal was as follows: at a late time after the direct sound during the decay of sound, the instantaneous sound level throughout the space is constant. The total reflected sound level decreases therefore with increasing distance because reflected sound at individual positions cannot arrive at the listener before the direct sound. This line of reasoning leads to the following relationship for the total reflected sound level:

$$L_{refl} = 10 \cdot \log\left(\frac{31200 \cdot T}{V}\right) - \frac{0 \cdot 174 \cdot r}{T} \text{ dB} \tag{1}$$

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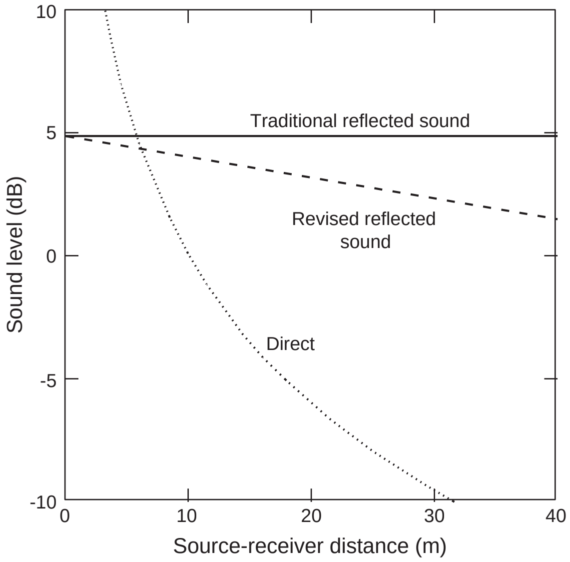

Fig. 1. Theory of sound level in a room with a point source.

where T is the reverberation time (RT), V the auditorium volume and r is the source–receiver distance.

Fig. 2 shows a typical variation of sound level (including the direct sound) with distance in a large concert hall. Fig. 3 shows the agreement between measured and predicted sound levels in 17 concert halls, with the direct sound according to the inverse square law and reflected sound level according to Eq. (1). In Figs. 2 and 3, under-balcony positions have been omitted as these tend to have lower sound levels than fully exposed locations. The correlation coefficient between measured and theory in Fig. 3 is $r = 0.94$; the root mean square error is 1.1 dB. The revised theory of sound level thus represents average behaviour well.

Thus in a concert hall with a typical reverberation time of 2.0 s, for receiver positions well away from the source (where the contribution of the direct sound is no longer significant) the rate of decrease of sound level from Eq. (1) is 0.087 dB/m.

3. Sound level in practice

The implication of the $G \geqslant 0$ dB criterion for strength in terms of the limits for concert hall dimensions is of interest. The reverberation time of most major concert halls is around 2.0 s. A maximum of 3000 seats is frequently mentioned for concert halls, as is the requirement of 10 m^3/seat. Thus we have a maximum volume of 30,000 m^3. The maximum recommended distance in a concert hall is 40 m from the stage to the farthest seat. These values for T, V and r give a value for G (Direct sound level + L_{refl} from Eq. (1)) of 0.0 dB. Thus general values for reverberation time and volume per seat for large concert halls, plus maximum values for seat capacity and distance lead to $G = 0$, which provides support for the proposed minimum value for strength.

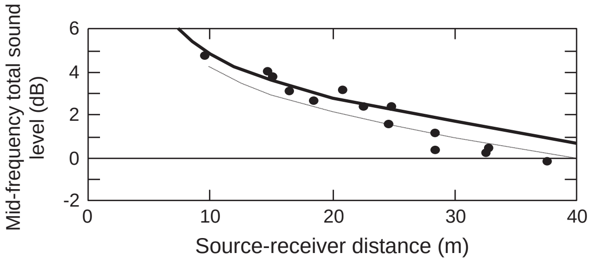

Fig. 2. Measured sound level in a large concert hall, compared with revised theory (solid line). Positions under balcony overhangs have been omitted. Measured values have been corrected to occupied conditions for the RT change. Dotted line is the new minimum criterion.

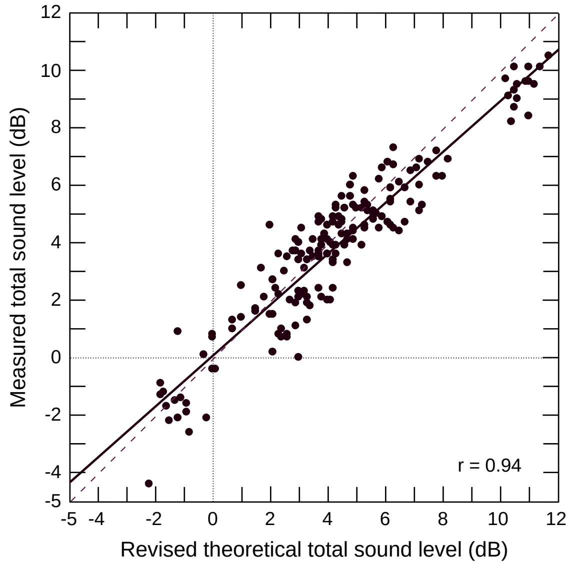

Fig. 3. Measured vs. revised theoretical total sound level at mid-frequencies. 174 Positions in 17 concert halls, omitting under-balcony locations.

Though the discussion of sound level in concert halls above has concentrated on behaviour with distance, the prime determinant remains the total acoustic absorption, A m^2 (which from the Sabine equation is proportional to V/T). It is because of this that there is a limit on the number of seats in concert halls. The Royal Albert Hall in London has an audience capacity of over 5000 seats. Fig. 4 shows measured values of the total sound level in this hall, which have been corrected from the unoccupied reverberation time at the time of measurement to the occupied value. At most measurement positions, the measured values are reasonably similar to those predicted by revised theory (given by the solid line). However the high acoustic absorption means that measured values are all below the 0 dB criterion with the exception of the measurement position close to 10 m from the source.

4. Loudness in concert halls

Evidence that loudness was an important issue for concert hall listening emerged in two German subjective studies in the late 1960s and early ‘70s. Both groups were conducting experiments using recordings via dummy heads made in a range of concert halls. The Göttingen group [7] were using paired comparisons by

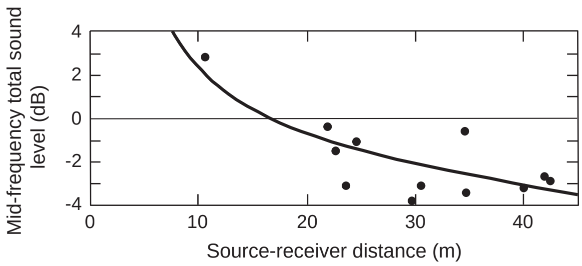

Fig. 4. Measured total sound level at mid-frequencies in the Royal Albert Hall, London. Measured values have been corrected to occupied conditions for the RT change. Solid line gives revised theory predictions.

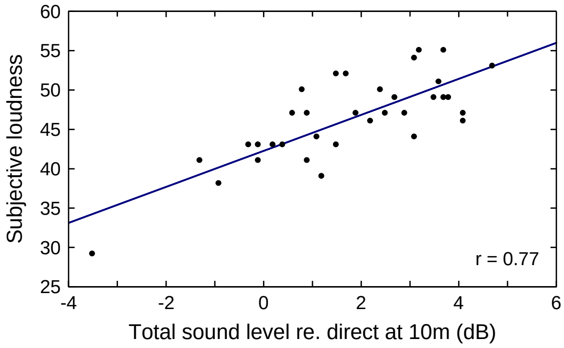

Fig. 5. Subjective loudness plotted against measured sound level at frequencies 125–2000 Hz.

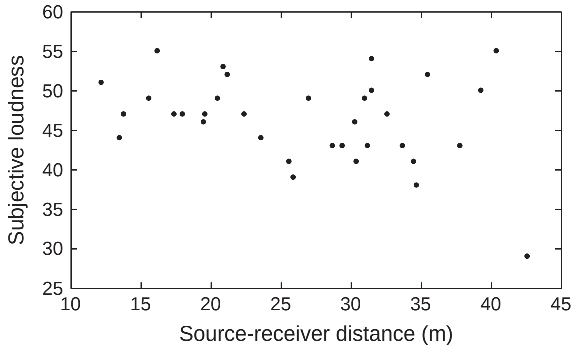

Fig. 6. Subjective loudness plotted against source–receiver distance.

subjects and found that loudness dominated preference; they therefore adjusted the sound level of their recordings to eliminate loudness differences from their experiments! The Berlin study [4] involved subjects completing questionnaires; factor analysis indicated that 'loudness' was one of three subjective factor scales. Perceived loudness was found to be strongly correlated with total sound level ($r = 0.82$) [8,p.603].

In this author's subjective study [9], in which listeners completed questionnaires during actual concert performances, both subjective 'intimacy' and 'loudness' were found to be correlated to measured total sound level. Interestingly 'intimacy' was better correlated with 'overall acoustic impression', the subjective measure of preference. The following is based on the results of this study regarding 'loudness'. Several results presented here have already been quoted in Ref. [3]. In the latter paper, the regression coefficients, which are also those quoted here, are slightly different to those quoted in [9]. The data set in [9] used a minimum of three questionnaires per seat position. Further subjective tests were conducted later in some of the concert halls and data presented here is from a revised data set with a minimum of four questionnaires per position. This revised data set contains results from 34 positions in 11 large British concert halls; all these halls have an audience capacity greater than 1500. Both data sets lead to the same conclusions regarding loudness.

Fig. 5 shows the relationship for the author's data between subjective loudness and full-frequency sound level, with a correlation coefficient of $r = 0.77$ (the correlation coefficient with mid-frequency level was $r = 0.70$). These coefficients are comparable to that quoted for the Berlin study above.

5. Loudness and distance

5.1. Subjective and objective data from actual concert halls

For the same data set, objective measured full-frequency sound level is correlated with source–receiver distance ($r = -0.66$). Loudness however is not significantly correlated with source–receiver distance Fig. 6 ($r = -0.31$). This is slightly surprising.

If a multiple regression is performed on loudness, it is found that the coefficient is improved from $r = 0.77$ to $r = 0.82$ if both sound level and distance are included. The regression equation is:

$$\text{Loudness} = 2.96 \times (\text{Full-freq. sound level} + 0.076 \times \text{Distance}) + 35 \qquad (2)$$

The crucial observation here is the sign of the coefficient for distance: loudness apparently increases with distance. Since sound level decreases with distance, we might have expected the relationship between loudness and distance to be the other way round.

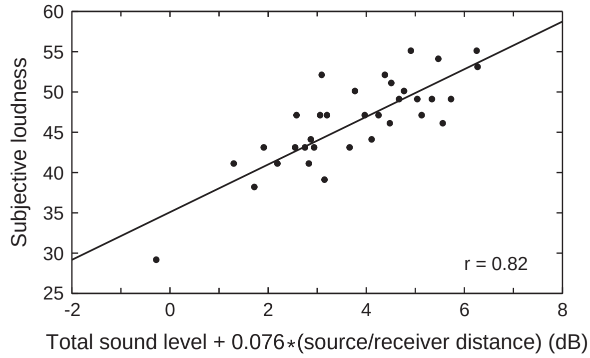

Fig. 7. Subjected loudness plotted against total sound level and a contribution from distance.

There is no obvious objective behaviour which explains loudness increasing with distance. The most persuasive explanation is the subjective one: that listeners relate their judgement of loudness to how far they judge themselves to be distant from the stage. Fig. 7 shows the correlation between loudness and (Full-freq. sound level + 0.076 × Distance). Both this regression and that with sound level alone are significant at the 0.1% level.

To demonstrate the dependence on distance, one can plot loudness corrected for level against source–receiver distance Fig. 8. From Eq. (2), the corrected loudness here is (Loudness/2.96 − Full-freq. sound level). This shows that loudness on average does increase with distance. The correlation coefficient of $r = 0.51$ is significant at the 1% level.

From Eq. (2) the trade-off between level and distance is 0.076 dB/m. This is similar to the rate of level drop-off in halls of 0.087 dB/m, quoted in Section 2 above. The accuracy of the first of these numbers is not high, based as it is on subjective data. It

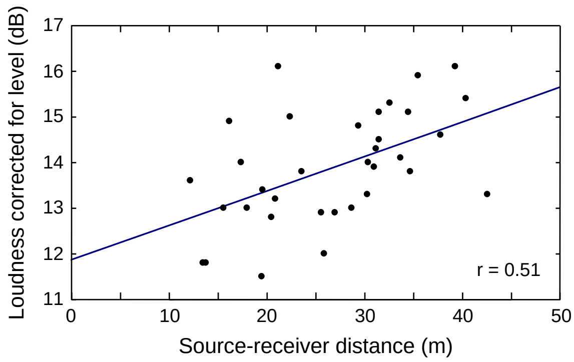

Fig. 8. Subjective loudness corrected for total sound level plotted against source–receiver distance (see text).

is therefore a reasonable assumption that listeners judge the loudness as roughly constant throughout a hall with the possible exception of positions close to the stage. We would also expect loudness to be judged lower at positions adversely influenced by design features, such as seats overhung by balconies.

5.2. Experimental psychologists and loudness constancy

Experimental psychologists have been interested in loudness constancy for a while now. As mentioned above, the most persuasive explanation is the subjective one: that listeners relate their judgement of loudness to how far they judge themselves to be distant from the stage. But this poses the question of how listeners are judging distance. One obvious possibility is that the acoustic judgement is being influenced by a visual cue. Sensual interactions have created an extensive literature in the experimental psychology field, such as [10].

Zahoric and Wightman [11] describe two interesting experiments which confirmed loudness constancy in the conditions they tested and that visual cues are not necessary. To eliminate visual cues they recorded binaural room impulse responses (BRIRs) at the subjects' ears in a small auditorium at different source–receiver distances. These were then used to generate stimuli with broadband noise bursts as an unfamiliar source signal. In spite of removing many cues that would be present in normal conditions, loudness constancy was confirmed. In addition, most estimates by subjects of apparent distance were found to underestimate the real distance.

Zahoric and Wightman discuss what cues listeners in their experiments may be using to judge loudness other than sound level. They suggest that reverberant level could be used as it is much more constant in level than the direct sound. However while it is true that the reverberant level varies less than the direct sound, the reverberant (late) sound does vary significantly. In the concert hall situation, revised theory of sound level predicts an average range for late sound (after 80 ms) at distances between 10 and 40 m of 2.6 dB for a reverberation time of 2 s (derived from Eq. (1), the second term in the equation is also relevant for late sound). Revised theory however ignores scatter and poor design, the mean range for late sound for the 16 concert halls considered in [12] is 5.2 dB. Ambiguity thus remains concerning the cues listeners are using for loudness judgement.

The small auditorium used in Zahoric and Wightman's experiments had a seating capacity of 264 and a reverberation time of around 0.7 s; source–receiver distances between 0.3 and 13.8 m were used, with a similar theoretical range for late sound. This obviously differs from a full-size concert hall, but these experiments provide valuable support to the growing evidence for loudness constancy in enclosed spaces.

6. A criterion for sound level

In halls we thus have sound levels that decrease with distance, whereas loudness remains basically constant, as sketched in Fig. 9. If the criterion of $G \geqslant 0$ dB is applied to the position with the lowest sound level, which is at a source–receiver distance around 40 m, then to maintain loudness at positions nearer to the stage, it is necessary for the sound levels, G, to be greater than 0 dB at distances less than 40 m. Only in this way will the loudness be judged as adequate. It is however fair to add that loudness judgements close to the source (stage) may not remain constant with distance; the subjective situation becomes more complex here with the varying distance to different members of the orchestra.

This line of argument therefore leads directly to a modified sound level criterion. In Section 3, the sound level in a hall with

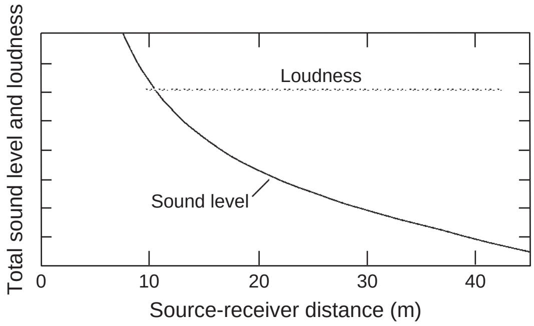

Fig. 9. Behaviour of subjective loudness and total sound level as a function of distance.

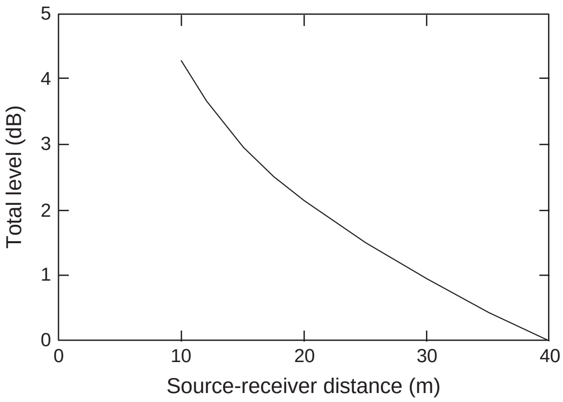

Fig. 10. Proposed minimum value for strength (G) as a function of source–receiver distance.

reverberation time of 2 s and a volume of 30,000 m^3 is predicted to be 0 dB at 40 m. The minimum criterion for G then becomes the predicted sound level for this particular hall, as shown in Fig. 10. The equation of this line is:

$$L = 10 \cdot log(100/r^2 + 2.08 \cdot e^{-0.02r}) \quad (3)$$

As an example of the implications of the new criterion, in the case of the measurements in the hall in Fig. 2, the new criterion suggests that 4 out of 14 positions are too quiet, as opposed to one for the old criterion.

7. Conclusions

Objective measurements in concert halls have shown that sound level, relative to a standard sound power source, decreases with distance more than had been traditionally believed. On the other hand, assessment of subjective loudness indicates that loudness judgement is almost independent of distance from the stage, which suggests that listeners are compensating their judgement of loudness on the basis of either visual or other aural information. These two results lead to a criterion for the minimum sound level in concert halls, which instead of being a single value, $G \geqslant 0$ dB, is a function of distance, as shown in Fig. 10 and analytically in Eq. (3).

It is valuable, with a result such as this, for it to be confirmed by subjective observation. Loudness judgements are needed from listeners at seats where the measured level G is greater than 0 dB but less than the curve in Fig. 10, to establish whether in fact sound here is judged as too quiet.

There are several possible mechanisms by which listeners may be compensating for distance. To date the question of how it is likely to be done in a concert hall environment appears to be unresolved.

The usual concern in large concert halls is for the loudness to be sufficient. Loudness overload does in fact also occur, particularly when a professional orchestra plays in smaller halls (less than 1000 seats). There is a strong case for some variable absorption in these halls.

This paper has been concerned with loudness perception and its link to sound level in halls. A closely related subjective phenomenon is ‘intimacy’, which is also found to be related to measured sound level [9], though not to distance in the same way as loudness. Some uncertainties remain regarding objective correlates of ‘intimacy’; Hyde [13] has provided an interesting discussion of this.

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