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Natural speech intelligibility in theatres in relation to its acoustics

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ABSTRACT

There is a certain tendency in the design of theatres to make the halls quite large. From a perspective of natural speech intelligibility and strength of speech this is disadvantageous, because an actor's voice has a certain, limited loudness and consequently the signal-to-noise ratio at the listener may become too low. Based on the influence of signal/noise ratio on speech intelligibility, it is deduced that the strength G≥6 dB and room volumes have to be limited to 4000-4500 m^3 in order to maintain sufficient loudness for natural speech. Sound level measurements during performances with natural speech in a theatre have been performed, to determine background noise levels in the hall due to the audience and to investigate the signal-to-noise ratio of the actors voice at the audience. The background levels are mainly determined by installation noise and not by the influence of the audience.

NATURAL SPEECH

Intelligibility of non-amplified, "natural" speech can be considered as a primary requirement for theatres. Compared with amplified speech, natural speech provides more intimacy and involvement with the actors, a more natural room impression, a better acoustic localisation of the actor matching the visual localisation. When designing theatres the intelligibility of natural speech should therefore be the key design parameter and not only reverberation time.

Intelligibility and ALcons

A true measure for the speech intelligibility is the parameter AL_{cons} (Articulation Loss of Consonants). This is the percentage of wrongly understood consonants to be determined by test persons, because they are the ones who understand. The speech intelligibility is not only determined by the transmission channel (e.g. the room), but also by speaker-listener effects (proficiency of speaker, complexity of message, familiarity with content etc.). The speech intelligibility can be judged as good if the AL_{cons} value is below 10%, reasonable if between 10 and 15% and bad above 15%.

In 1971 V.M.A. Peutz has proposed a simple prediction method for speech intelligibility in rooms, expressed in AL-cons. Peutz presented a set of equations to predict AL_{cons} from a few easily assessable acoustical parameters [1]. Up to a critical distance for intelligibility (D_c) the AL_{cons} increases quadratically with distance:

$$D_c = 0.2\sqrt{\frac{QV}{T}}\,[m] \qquad (1)$$

$$AL_{cons} = \frac{200\,D^2\,T^2}{Q\,V} + a\,[\%] \qquad (2)$$

with:
D = distance to the source (m)
Q = directivity of the source (@1.4 kHz)
T = RT_{60}= reverberation time of the room @1.4 kHz (s) or the average of 1 kHz and 2 kHz octave bands.
V = room volume (m^3)
a = zero correction factor for a certain speaker-listener combination (proficiency) usually between 1.5% and 12.5%. In AL_{cons} graphs a theoretical ideal value of a=0% is implicitly assumed.

For $D \geq D_c$ AL_{cons} has a constant value:

$$AL_{cons} = 9\,T + a \quad [\%] \qquad (3)$$

The maximum value for AL_{cons} is limited to 100%. In figure 1 the relation between AL_{cons} and D/D_c is graphically shown for several values of T.

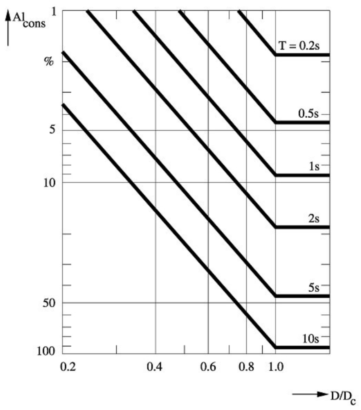

Figure 1. AL_{cons} as a function of D/D_c and T [1]

In theatres the value for D_c usually is between 10-15 m, depending on the position, direction and directivity of the source. Because usually the audience is partly seated beyond this distance, and these parts are most critical regarding speech intelligibility, distances above D_c will be regarded further.

Strength and room absorption

To fulfil the requirements for a good intelligibility of AL_{cons} ≤10%, the reverberation time T should be below 1.1 s. according equation 3, assuming an ideal theoretical value of a=0%. If a practically more realistic value for the factor a is assumed, for instance a=2%, the reverberation time T should not exceed 0.9 s (1-2kHz). Slightly lower values of T down to 0.8 s will be appreciated in smaller theatres for optimal speech intelligibility. However, usually lower values for T should be avoided because this leads to increased values for the average room absorption α_{room} and a reduction of the strength G, thus compromising the strength for natural speech. Alternatively the room volume should be kept as small as possible. This will be illustrated next.

For a cubic volume V (m^3) the total surface area of walls, floor and ceiling S_{tot} (m^2) is:

$$S_{tot} = 6 * \left(\sqrt[3]{V}\right)^2 \qquad (4)$$

The average room absorption α_{room} can be written as:

$$\tilde{\alpha}_{room} = \frac{A}{S_{tot}} = \frac{V}{6\,T\,S_{tot}} = \frac{\sqrt[3]{V}}{36\,T} \qquad (5)$$

From equation 5 it can be seen that the average room absorption does not only depend on T but also on the room volume. The strength or gain G (dB) can than be written as:

$$G = 31 - 10\log\left(\frac{S_{tot}\tilde{\alpha}_{room}}{4(1-\tilde{\alpha}_{room})}\right) \qquad (6)$$

The factor (1- α_{room}) represents the amount of sound energy of the source that is not absorbed by the first reflection but goes into the room and "becomes" reverberant energy [2]. Equation 5 and 6 can be graphically represented in a so-called G-RT plot in figure 2. In this graph also some design-lines for concert halls [3,4] and rehearsal rooms [5] are drawn.

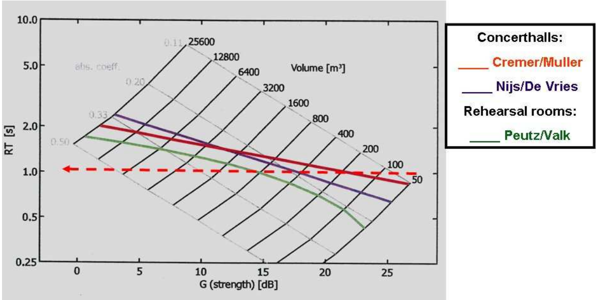

Figure 2. G-RT plot with some design lines [3,4,5]

A red dotted line is drawn in figure 2 to illustrate that if the demand of T≤1.0 s for a theatre has to be fulfilled and the room volume increases, α increases accordingly and the strength G decreases significantly.

AL_{cons} and noise

Equations 2 and 3 do not incorporate the influence of noise on speech intelligibility and AL_{cons}. Based on experiments in years before 1970, Peutz stated that equation 3 was only valid for a signal-to-noise ratio (S/N) of 25 dB or higher. For S/N≤25 and D≥D_c he proposed a relation that is graphically represented in figure 3 [1], where AL_{cons} increases exponentially with decreasing S/N.

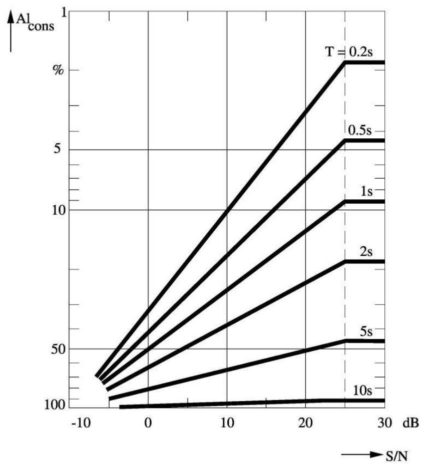

Figure 3. Al_{cons} as a function of S/N and T [1]

This exponential relation between AL_{cons} and S/N can be described by:

$$AL_{cons} \approx (100-a)*10^{\left(\left[\frac{Lp_s - Lp_n + 10}{35}\right]*(1+\log(0.009T))\right)} + a \qquad (7)$$

with:

Lp_s = lineair speech level at listener (dB). This is the sum of the direct (Lp_d) and reverberant (Lp_r) sound (wide band or A-weighted value, for natural speech these have almost the same value [6]).

Lp_n = noise level in PSIL (preferred speech interference level), which is the average level of the 500 Hz, 1kHz and 2 kHz octaves. This level is usually 5-6 dB lower than the A-weighted level [6].

If S/N is expressed in dB(A) instead of PSIL, the slope of figure 3 will start at S/N=20 dB(A) instead of at S/N=25. Also equation 7 is limited to T≤11 s, otherwise the term between brackets would become positive and the AL_{cons} would increase with S/N.

Figure 4 gives the similar relation as in figure 3, but focusses on values of T (1-2 kHz) that occur in theatres.

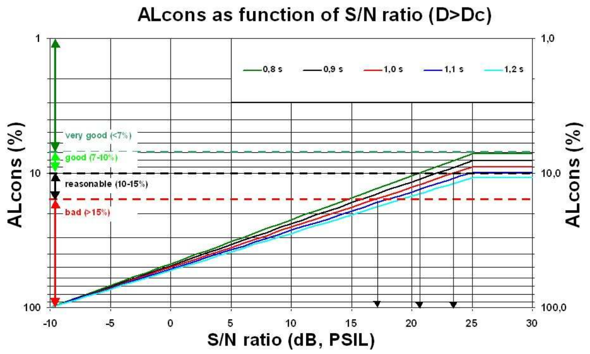

Figure 4. AL_{cons} as function of S/N for 5 values of RT.

Figure 4 illustrates that in a theatre with 1.0 s reverberation time, the S/N has to exceed 17 dB to achieve a reasonable speech intelligibility for $D \geq D_c$, and S/N≥23 dB for a good speech intelligibility, assuming an ideal theoretical value of a=0%. With a reverberation time of 0.8 s a 3 dB lower S/N is allowable for the same intelligibility, thus allowing a higher tolerance for noise. This is another reason to aim for 0.8 s reverberation time in a theatre. For reverberation times above 1.0 s and $D \geq D_c$ only a reasonable intelligibility is achievable.

If a practically more realistic value for the factor a is assumed, a higher S/N or a shorter reverberation time will be necessary to reach the same intelligibility. If for instance a=3% is assumed, it can be deduced from equation 3 that in order to achieve a good intelligibility ($AL_{cons} \leq 10\%$) for $D \geq D_c$ the reverberation time should not exceed 0.8 s and S/N has to be at least 25 dB.

Signal-to-noise ratio of natural speech in a theatre

The signal-to-noise ratio (S/N) of natural speech in a theatre can be described by the following equation:

$$Lp_s - Lp_n = L_w + 10\log Q_{source} - 31 + G_{theatre} - Lp_n \quad (8)$$

with:

L_w = linear sound power level of the actor (dB);

Q_{source}= the effective directivity of the source in relation to its direction to the listener. In a situation where an actor (Q=2.5) is speaking 90° off axis (not facing the listener) a effective value of Q_{source}=1 towards the listener can be assumed;

$G_{theatre}$= the effective strength of the theatre at a certain listener position for an omnidirectional source at a specific source position, including the energy loss into the stage area. Unlike G in a concert hall, $G_{theatre}$ depends on the position of the source relative to the stage opening. Usually an averaged G value is calculated that has been averaged over the measuring positions beyond 10m distance of the source.

Assume a theatre with a background noise level with audience of Lp_n = 25 (PSIL), a reverberation time of 1.0 s and an actor speaking 90° off axis at a normal level with L_w= 70 dB and a=0%. Based on equation 7 and figure 4 the minimal requirement should then be S/N≥17 to achieve a reasonable speech intelligibility ($AL_{cons} \leq 15\%$). This means that the required speech level should be $Lp_s \geq 42$ dB. Equation 8 then becomes:

$$G_{theatre} \geq +3 \quad [dB] \quad (9)$$

This has certain consequences for the design of theatres. These will be discussed further, after the introduction of a parameter Q_{stage}.

Q_{stage} for theatres

Usually there is a direct (sight-)line between the source (mouth/head of actor) and the listener, so the direct sound from the source to the listener is usually not obstructed. In many situations and for several seats the direct sound may be too weak, and the reverberant level becomes of major importance for speech intelligibility. This reverberant sound level depends on reflections in the hall.

Unlike a concert hall, a theatre usually has two coupled volumes, the hall and the stage. For any source position on stage, a certain part of the source-energy will radiate into the stage area and will be almost completely absorbed, either by the stage curtains or by the walls or the ceiling of the stage tower. This part of the source's sound energy will not be reflected into the hall and will therefore not contribute to the reverberant sound level in the hall. The remaining part of the source energy radiates directly into the theatre through the stage opening, and determines the reverberant level in the hall. The ratio between both energy parts depends mainly on the opening angle of the source into the theatre, but also on the source directivity and direction, the source position and the size of the stage opening. This ration can be quantified using a new parameter Q_{stage}. This is the directivity factor of the relative opening angle of the source to the hall ("room"). A longer subscript using "$Q_{source\text{-}stage}$" would perhaps be more clear, but for reasons of simplicity Q_{stage} will be used further.

In figure 5, a ground plan is given of theatre De Spiegel in Zwolle (NL), in theatre-mode. On stage the stage curtains are schematically drawn. Four different source positions are indicated on stage together with the resulting opening angles through the stage opening. The resulting values for Q_{stage} are also indicated. These values depend strongly on the source position (forestage, backstage).

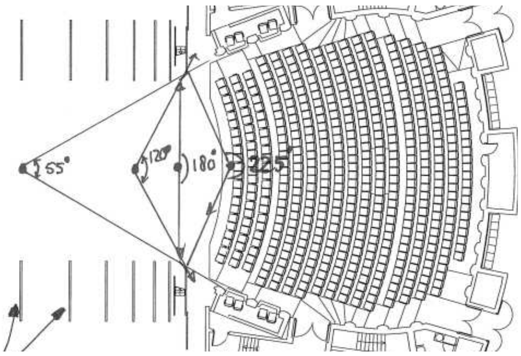

Figure 5. Ground level plan of theatre "de Spiegel" in Zwolle. The horizontal opening angle to the hall (β) is indicated for 4 different source positions.

In figure 6 a cross-section of the same theatre De Spiegel in Zwolle is given, with the hall set in theatre mode. The movable ceilings are drawn at the corresponding lowest height, thereby limiting the volume of the hall to 3,500 m^3 and reducing the reverberation time to 0.9 s. [8]. In this cross-section, the same four different source positions are indicated on stage together with the resulting opening angles through the stage opening and the resulting values for Q_{room}

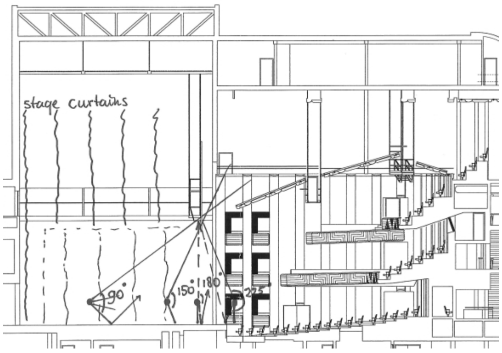

Figure 6. Cross-section of theatre “de Spiegel” in Zwolle. The vertical opening angle to the hall (γ) is indicated for 4 different source positions.

Figure 6 also illustrates that the sound-reflective stage floor is acoustically usefull. Depending on the source position, all floor reflections that enter the hall through the stage opening will contribute to the reverberant level in the hall. Also some floor reflections will cause a strong early reflection towards specific listeners shortly after the direct sound, thereby improving the (early) sound level and intelligibility.

For an omnidirectional source, the directivity factor of the relative opening angle of the source to the room (Q_{stage}) can be calculated based on the opening angles in the horizontal and vertical plane, according:

$$Q_{stage} = \left(\frac{\Omega}{4\pi}\right) \approx \frac{\beta}{360} * \frac{\gamma}{180} \qquad (10)$$

with:

Q_{stage}= directivity factor of the relative opening angle of the source to the hall
β = horizontal opening angle towards stage opening
γ = vertical opening angle towards stage opening
Ω = solid angle, which fulfils:

$$\Omega = \int_0^{\beta}\int_0^{\gamma} \sin\theta \, d\theta \, d\phi \qquad (11)$$

If a directional source is used, determination of Q_{room} becomes more elaborate, and a more precise integration should be performed of the angle dependant sound intensity ($L_I(\theta,\phi)$) multiplied by the surface area to deliver the relevant part of the total sound power level (L_w) radiating into the hall.

Energy loss of the source into the stage area

The reduction of the reverberant sound level (Lp_r) in a theatre compared with the value of Lp_r of the same source in a single volume, can be calculated using the factor “$10\log Q_{stage}$”. Consequently $G_{theatre}$ can be calculated as:

$$G_{theatre} = G + 10\log Q_{stage} \qquad (12)$$

With:

G = strength factor as a measure of the sound-pressure level at a point in a hall with an omni-directional source on stage, minus the sound pressure level of the same source at 10 m distance in an anechoic chamber or free field [7], expressed as:

$$G = 10\log\frac{\int p^2(t)dt}{\int p_{10}^2(t)dt}[dB] \qquad (13)$$

or:

$$G = L_p - L_w + 31 \quad [dB] \qquad (14)$$

Implicitly G is independent of source position, because it is originally defined for concert halls where all source energy is emitted into the volume of the hall.

In table 1 the values of several parameters regarding the different source positions in the situation of figure 5 and 6 are summarised, together with the energy loss for an omnidirectional source according equations 10 and 12.

Table 1. Factors determining the energy loss of an omnidirectional source into the stage area for 4 different source positions (see figure 5 and 6)

Source position relative to stage opening (m)	Opening angles (hor; vert. (°))	Q_{stage}	Energy loss $-10\log Q_{stage}$ (dB)
+3	225; 225	0.76	-1.1
0	180; 180	0.5	-3
-3	120; 150	0.28	-5.5
-10	55; 90	0.08	-11

From table 1 it can be seen that from the four different source positions, the source position on the forestage is the only one that leads to a limited reduction of reverberant sound level in the hall (-1.1 dB). With the source in the stage opening 3 dB is lost, and for positions more backwards even higher energy losses occur.

In case of a directional source, for instance a human voice, significant reductions of reverberant energy should also be accounted for. The usual directivity of a human voice is Q_{source}=2.5 (on axis). During a performance however an actor is not always facing the same listener, and is regularly speaking to the side, facing 90° off axis. In this case an effective directivity to the listener of Q_{source}=1 will be appropriate. Assuming this directivity and a position of the actor in the stage opening, the value of Q_{stage} will be 0.5, and an energy loss of –3 dB should be accounted for according equation 12.

Design values for G and V of a theatre

Because of the reduced reverberant sound level in a theatre, caused by the energy loss of the source into the stage area, a higher value of G has to be required in the design of a theatre, to compensate for this loss. A compensation of at least +3 dB seems reasonable regarding table 1, assuming an average source position around the stage opening. Using this correction together with het previous equations 9 and 12, it can be deduced that, in order to realise at least a reasonable speech intelligibility for $D \geq D_c$, the design value of G has to fulfil:

$$G \geq +6 \quad [dB] \qquad (15)$$

Only when regularly using forestages lower values of G may be allowed.

Based on equation 15 the allowable room volumes for theatres can be deduced. Assuming a simplified cubic volume for which the equations 4 to 6 are valid, a standard G-RT plot can be used. In figure 7 this plot is graphically represented, together with the two boundary lines for designing theatres: Under the red horizontal line is an area for which applies: T≤1.0 s (AL_{cons}≤10%). To the right of the vertical line is an area for which applies: G≥6 dB. When both requirements are combined, the result in an area with sufficient speech intelligibility, indicated by the grey rectangle in figure 7.

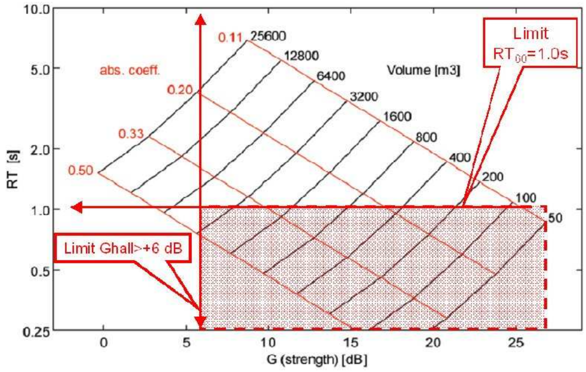

Figure 7. G-RT plot with 2 boundary-lines for theatre (T<1.0 s, G≥6 dB).

However, not every position in the shaded part of figure 7 is suitable for theatre-use. A value for T=0,5 for a 3500 m^3 theatre, for instance, is undesirable. A further division therefore is desirable. With reference to the logarithmic design relations between T and V as used for concert halls and rehearsal rooms (see figure 2), the following relation between T and V for rooms suitable for natural speech is proposed:

$$T = 0.417 \log V - 0.55 \quad (16)$$

In figure 8 equation 16 is combined with the design area for sufficient speech intelligibility of figure 7. A good theatre for natural speech should be designed primarily within the resulting shaded green area.

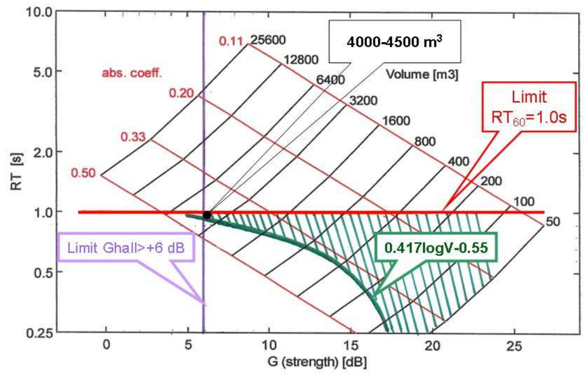

Figure 8. G-RT plot with 3 boundary lines for theatre design (T<1.0 s, G≥6 dB, eq. 16)

From figure 8 it can be concluded that the corresponding maximum volume for a theatre that has to fulfil the basic requirements as mentioned before, is in general about 4.000 to 4.500 m^3, under the assumptions made before. Specific adaptation of this value depending on the situation will however be necessary, because the G-RT graph of figure 8 is based on several simple relations (eq. 4 to 6), that are more complex in reality, as will be discussed next.

Adapted description of G and Lp_r

In reality there are usually two different average absorption coefficients, that are not necessarily the same: On one hand the average room absorption coefficient α_{room}, that is averaged over all room surfaces and that determines the reverberation time. On the other hand there is the average absorption coefficient as seen from the source α_{source} [9]. The factor (1- α_{source}) represents the energy ratio of the source as seen from the source that is not absorbed by the first reflection but goes into the room and "becomes" reverberant energy. Using a non-omnidirectional sound source α_{source} can be significantly higher than α_{room} in reality. The previous equation 6 should therefore be more precisely written as:

$$G = 31 - 10\log \frac{S_{tot}\alpha_{room}}{4(1-\alpha_{source})} \quad (17)$$

With:

α_{room} = average room absorption
α_{source}= average absorption seen from the source
S_{tot} = total surface area (m^2) of walls, floor, ceiling of the room.

In reality a hall or theatre usually does not have a cubic shape, so the value of S_{tot} can be different from the one following from equation 4.

Instead of using the general equation 17, that neglects the contribution of the direct sound, a more specific calculation of total sound level is usefull, and preferably its dependance with distance. The total sound level is the energetic sum of the direct sound L_{pd} and the reverberant sound level L_{pr}. The direct sound L_{pd} fulfils:

$$Lp_d = L_w + 10\log \frac{Q_{source}}{4\pi r^2} \quad (18)$$

At the critical radius R_c the direct sound and the reverberant sound have the same level. If the energy loss into the stage area is incorporated using the directivity factor Q_{stage}, R_c becomes dependent of the source position and fulfils:

$$R_c = \sqrt{\frac{Q_{source}V}{300T(1-\tilde{\alpha}_{source})Q_{stage}}} \quad (19)$$

The reverberant sound level at the critical radius is:

$$Lp_r = L_w + 10\log \frac{Q_{source}}{4\pi R_c^2} \quad (20)$$

or:

$$Lp_r = L_w - 10\log \frac{S\tilde{\alpha}_{room}}{4(1-\tilde{\alpha}_{source})} + 10\log Q_{stage} \quad (21)$$

In reality the reverberant sound level does appear not to have a constant value but decreases with distance [10], caused by a non-diffuse sound distribution. This decrease of the reverberant field with distance can be described by:

$$\Delta = \frac{k\sqrt{V}}{hT} \quad [\mathrm{dB}_{/\text{doubling of distance}}] \quad (22)$$

with:

k = constant or room type indicator (≅0.3±0.1)
h = room height (m)

If equation 19 is compared with equation 1, it can be deduced that D_c is 3,16 times the critical radius R_c, provided α_{source}=0,17 and the reverberant level is constant. In reality D_c (where Lp_d/Lp_r=-10) will be larger, because the reverberant level is not constant but decreases from R_c according equation 22.

The energy loss of the reverberant sound level into the stage area is not implemented in a standard G-RT plot, but can be incorporated implicitly by requiring a higher value for G compared with the real value in the theatre ($G_{theatre}$), as is done by transferring equation 9 into equation 15.

Application for two different theatres

The theory and equations as mentioned and explained before, have been implemented to compare two different theatres:

Picture an intimate, compact theatre (A) with a small volume of V=2.800 m^3, 650 seats, optimised sightlines (minimally sloped floor profile) and three balconies. Its room volume per seat has a limited value of 4.3 m^3/pp.

Theatre B is a flat-floored theatre with a retractable bleacher and the same amount of seats (650). Due to its design, theatre B has no balconies. Due to the addititional height required for theatre technical bridges the volume of the audience part is much larger than theatre A, and is 7.000 m^3. The volume per seat for theatre B is rather large for a theatre for natural speech (11 m^3/pp).

In figure 9 and 10 the floor plan andd the cross-section of both theatres is schematically drawn.

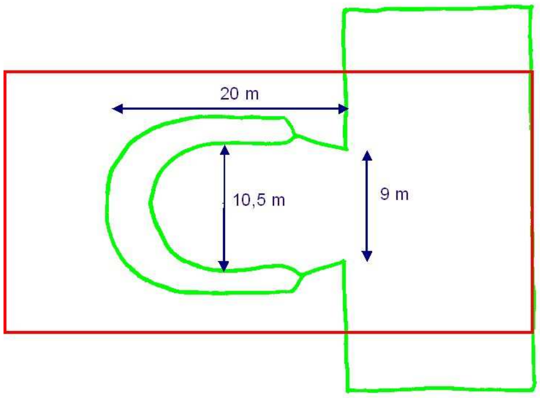

Figure 9. Schematic ground plan of theatre A (green) and theatre B (red)

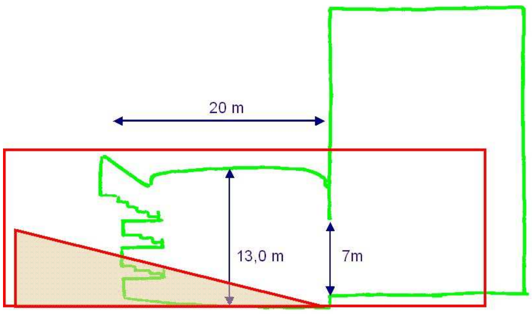

Figure 10. Schematic cross-section of theatre A (green) and theatre B (red)

Assuming that both theatres will have the same reverberation time (T=0.9 s), theatre B will need to have more absorbent walls to reach this reverberation time and consequently has a higher value for α_{room}. Theatre B will also have a higher value of α_{source} due to the steep audience arrangement. According equation 21 both higher values reduce Lp_r compared with theatre A, which is unbenificial for the strength of natural speech. The several input parameters and calculated parameters have been summarised in table 2.

Table 2. Data of two different theatres (see figure 9 and 10)

Parameter	theatre A	theatre B
V (m^3)	2,800	7,000
n (seats)	650	650
h (m)	12	14
T_{60} (1 kHz)	0.9	0.9
Q_{stage}	0.5	0.5
α_{source}	0.15	0.45
α_{room}	0.35	0.55
G (dB)	+7	+2
Resulting values with source in middle of stage opening:		
$G_{theatre}$ (dB)	+4	-1
R_c (m)	4.9	9.7
D_c (m)	15.8	25
3.16*R_c (m)	15.6	31
D@ Lp_d/Lp_r =-10 dB (m)	20	45

If a G-RT plot is used, resulting values for both theatres G=7 dB for theatre A and G=2 dB for theatre B, as is indicated in figure 11. However, these are not the actual strength-values that will be measured in these theatres, due to several simplifications in the G-RT plot as discussed before: The energy loss into the stage area is not implemented, the decrease of the reverberant level is not implemented, seperate values for α_{room} and α_{source} cannot be implemented.

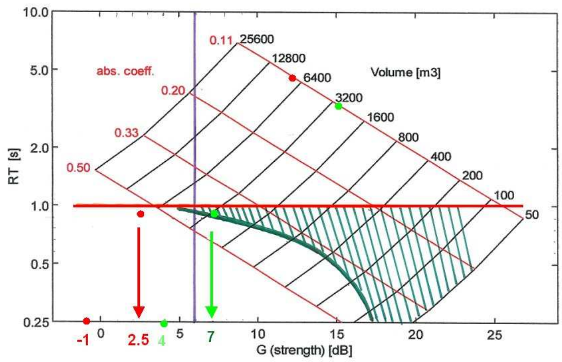

Figure 11 G-RT plot with indicated position of theatre A (green points) and theatre B (red point)

In order to evaluate the resulting sound levels and corresponding values for strength more precisely than based on a G-RT plot, the actual decrease of sound level with distance should be calculated with implementation of the adaptations as discussed before. Based on the inputparameter values in table 2 and equations 18 to 22, the decrease of the total sound level with distance has been calculated for the 1 kHz octave in both theatres. The relation between this total sound level and distance to the (point-)source is graphically represented in figure 12. In these graphs it is assumed both theatres that half of the source energy is lost into the stage area (Q_{stage}=2). In the graph the critical radius (R_c) and a value for D_c (@-10 dB) is indicated for both theatres. In table 2 several values for the expected critical distance are summarised, illustrating that actually D_c is not necessarily the same as 3.16 times R_c, nor similar to the –10 dB distance. For theatre B these distances are larger than in theatre A, due to the higher volume of theatre B. The expected background noise level is also indicated in the graph.

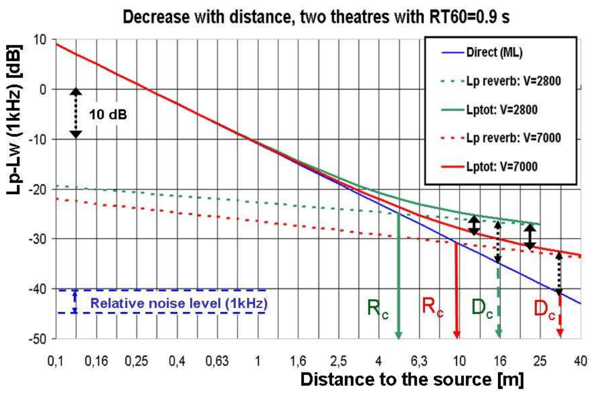

Figure 12 Decrease of sound level with distance calculated for two different theatres A (green) and B (red). The blue line gives an indication of expected noise level, assuming a average speaker as source.

From the calculated decrease with distance as given in figure 12, the G values (@1kHz) in both theatres can be derived. Also the averaged G value (@1kHz) for positions above 10 m distance from the source can be calculated. The resulting averaged G-values become G=4 dB for theatre A and G = - 1 dB for theatre B. Clearly there is a significant level difference noticeable between theatre A and B for similar listening distances. In the rear seats of theatre B the sound level is even lower than at 10 m distance in a free field.

These resulting (averaged) G-values can not directly be derived from the G-RT plot as is indicated along the x-axis in figure 11.

Figure 12 also illustrates that if the background noise levels are 40 to 45 dB below L_w, as can be expected in theatres assuming a source power level of a speaker of L_w=65-70 dBL, the resulting S/N in theatre B will become lower than 10-15 (@1kHz) or 15-20 PSIL. For distances beyond D_c a reasonable speech intelligibility than is no longer achievable (see figure 4). For distances closer than D_c the detrimental effect of the limited S/N ratio on the intelligibility will however partly be compensated due to the contribution of the direct sound.

S/N measured during theatre performance

To gain practical data about the actual speech levels and background noise levels in theatres during performances, several measurements have been performed.

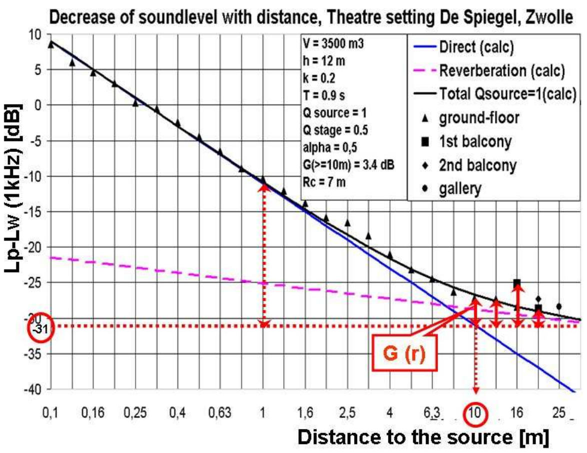

Figure 13. Decay with distance in theatre De Spiegel in Zwolle in theatre-mode, measured with an omni-directional source in the stage opening.

Theatre "De Spiegel" in Zwolle (NL) has a room volume of 3,500 m3 and 0.9 s reverberation, and is graphically represented in figure 5 and 6. The decay with distance measured with a point source on stage is graphically given in figure 13.

In this theatre sound level measurements have been performed during a theatre play with non-reinforced speech. In figure 14 several measurement of the equivalent sound level Leq are given.

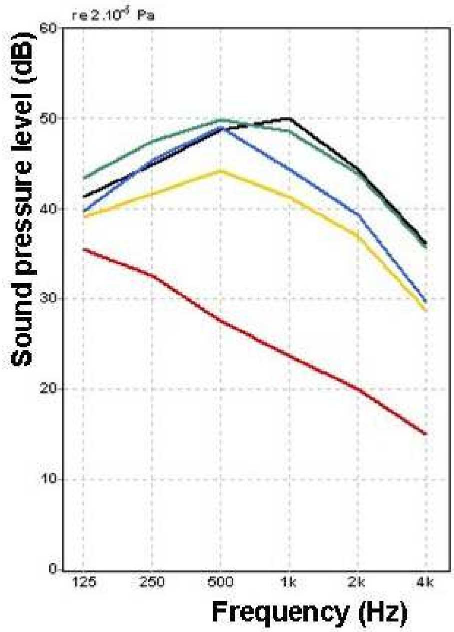

Figure 14. Measured sound level Leq @row 12 during a theatre performance with non-reinforced speech in theatre "De Spiegel" in Zwolle. Background noise level (red line) 24 dB (PSIL). Speech level (2-3 min each) 47-52 dBL. Yellow 47 dBL. Resulting S/N=23 dB PSIL.

The background noise level during the performance was about 24 PSIL or 30 dB(A). Based on the corresponding octave values it can be determined that for the softest spoken parts of the play the resulting S/N was 23 PSIL or 17 dB(A) at this specific listening position in this theatre. This means that for distances beyond D_c only a reasonable speech intelligibility can be expected. Because the measuring position at row 12 was well within a distance of D_c from the average actor's position, see figure 13, the actual speech intelligibility experienced at this position was good.

During the measurements the actor was moving around the stage and talking with a variable sound power level in different directions, so there is no specific source position with a fixed directivity, loudness, and corresponding Q_{stage}. A unambiguous determination of the actor's sound power level-based on the sound levels measured is therefore not possible. Visual recordings of the actors have not been made, so for each measurement assumptions have to be made for the actual source position, the related energy loss into the stage area as well as the source directivity and direction. Based on figure 13 with the decay with distance measured in this theatre a level decrease at row 12 of L_p=L_w-27 dB does occur. From the speech levels measured as given in figure 14 an indication for the sound power level of the actors can be deduced, that results in a value of L_w=73 to79 dB(A) assuming an average directivity towards the measuring position of Q_{source}*Q_{stage} =0.5, for instance Q_{source}=1 and Q_{stage}=0.5. Values of L_w=68 to 74 dB(A) can be deduced if Q_{source}*Q_{stage} =0.33 is assumed during the performance.

In future measurements additional visual recordings of the performance should be performed to get a more explicit feedback about the actual source position during the performance, and to obtain unambiguous data about the relation between the sound levels measured and the actor's position, loudness and direction.

Conclusions

The AL_{cons}- method gives an interesting possibility to deduce design guidelines for theatres suitable for natural speech. The preferred reverberation time for theatre should be 0,8-0,9 s, and its volume limited to 4000-4500 m^3. To obtain sufficient signal/noise ratio in theatres the sound energy loss into the stage area should be minimised, by applying a forestage as well as minimising the space for technical equipment directly behind the stage opening, so that actors can approach the stage opening closely. On the other hand sufficient gain of the room itself is necessary ($G \geq 6$ dB), the preserve as much the strength of the actor's natural speech and give sufficient feed back to the actor. Absorption of sound by audience and the walls should therefore be minimised, using low absorption of the walls and a limited slope of the audience arrangement. Sound level measurements during performances with natural speech in a theatre have been performed, to determine background noise levels in the hall due to the audience and to investigate the signal-to-noise ratio of the actors voice at the audience. The background levels are mainly determined by installation noise and not by the influence of the audience. In theatres with a larger volume than 4500 m^3 a reduction of speech intelligibility could be partly compensated by lower background noise level and/or by larger amount of seats within D_c. When measured values for G are presented, data about the source position and measuring distance(s) should be given as well to perform valid comparisons.

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