IS REVERBERATION TIME ADEQUATE FOR TESTING THE ACOUSTICAL QUALITY OF UNROOFED AUDITORIUMS?

D Paini Politecnico di Milano - Italy
A Ch Gade DTU - Technical University of Denmark
J H Rindel DTU - Technical University of Denmark

1 INTRODUCTION

What is an unroofed auditorium? It can be any place whose roof is represented by the sky: a public square, a stadium, a courtyard, etc.; in general a space which was not built with acoustics in mind, but where music and speech may have nowadays a central role (a live concert, a political meeting, a fashion show, etc.) at least during some periods in the years (summertime).

Not having any a priori acoustical characteristics, or not revealing all those acoustical qualities that would/should be expected from a place meant for music and/or speech, is it correct to use all the acoustical parameters that we typically apply in closed spaces (such as concert halls, theatres, opera houses)? And which, among them, are the most accurate parameters to acoustically describe an open place?

This paper aims at illustrating whether reverberation time (EDT, T30) and other acoustical parameters, are suitable and sufficient for testing the acoustical quality of open performance spaces.

Simulations as well as measurements were carried out to study the acoustics especially of open squares surrounded by hard, vertical, reflecting building facades. Especially when concerts are amplified, a strong direct sound, the lack of early reflections and the presence of few strong late reflections (often perceived as echoes or even flutter echoes) are often found to be the most important characteristic – and problem! Therefore, emphasis was given to finding out an acoustical parameter – or a set of parameters - which could illuminate this problem.

At first, a comparison between a closed space designed for music (i.e. a concert hall) and an unroofed auditorium has been done: this is important to analyze all the analogies and differences between these two types of spaces, from the geometrical, acoustical, visual points of view (Table 1 – a, b, c).

1.1 Geometrical factors

Here is a resume of the main geometrical aspects that can characterize a space:

a)	***Concert hall / Auditorium***	***Public Square***
Shape	shoe-box, fan shape, etc.	shoe-box, circular, irregular shape, with/without arcades, long and narrow, always without ceiling

Volume	volume from 10.000 m^3 up to 28.000 m^3, with some exceptions, like the Royal Albert Hall (more than 85.000 m^3)	volume of 3.000 m^3 up to 50.000 m^3, even if it's difficult to talk about volume if the space is open…
Surfaces	surfaces are treated to control early and late reflections, to obtain acceptable values of reverberation, clarity, lateral fraction and to avoid echoes or even flutter echoes (seeFigure 3-a)	all the façades are vertical and reflecting, with some diffusion at high frequencies, the floor is reflecting, too, and the ceiling is represented by the sky, which is totally absorbing. This gives a 2D reverberation (see Figure 3, b)
Number of seats	600-3000 seats. There should not be a great different in terms of absorbing coefficient between occupied and unoccupied audience (chair are usually absorbent enough). (See Figure 4-a)	50-3000 seats/standing positions. Very often the audience is standing, without the possibility to seat down. In any case there is a great different, in terms of absorbing coefficients, between occupied and unoccupied audience area. (See Figure 4-b)
Audience surface/Seat	0,6 - 1 m^2/seat	0,2 - 3 m^2/seat
Volume/Seat	9 - 12 m^3/seat	10 - 25 m^3/seat

1.2 Acoustical factors

b)	***Concert hall / Auditorium***	***Public Square***
Curve decay	Usually linear (**Error! Reference source not found.**, a), coupling or sagging decay	Usually linear with a "step" (Figure 4 - b) or even sagging; after the direct sound, only few early reflections are possible, due to vertical façades which are in general too far from a large part of the audience. The main consequence is a rather long plateau at the beginning of the decay, which represents the delay between the direct sound and the first important reflection. High initial-time-delay gap
Impulse response	Early reflections, absence (normally) of echoes or flutter echoes (Figure 2-a)	It's very easy to detect echoes or even flutter echoes. As the ceiling-sky is totally absorbing many sound rays are lost after the first-second order, meaning that the number of rays/reflections arriving to the listener is very low if compares with those of a closed space (Figure 2, b)

Acoustical parameters (EDT/T30, T30, C80, etc.)	EDT/RT > 1 (usually). RT = 1,3 - 2,2 sec. C80 = -5 and +3 dB[7]	EDT/T30 < 1 (usually). A part for the direct sound, late *strong* reflections are a typical characteristic of open public places. RT = 1,5 - 6,0 sec. C80 = 2 -7 dB[1]
Presence or not of echoes/flutter echoes	In general echoes, flutter echoes, as well as focused reflections should be/are avoided	Echoes and flutter echoes are the main problems, and it's difficult to avoid them, in principles
Amplification	Classical concerts are almost never amplified, but some reverberation can be added in some part of the audience. Pop concerts in concert hall are always amplified (with high SPL); too high RT for that kind of music and bed intelligibility	Classical concerts have to be amplified: problems to the musicians in hearing each other are frequent. Pop concerts are always amplified: echoes and too high SPL, which is needed to reach all the audience are the main consequences
Background noise	Background noise can only be represented by the air-conditioning system. Silencers and low air speed are good solutions to have a low background noise. A Noise Criteria NC = 15 to 25 is recommended[4]	Background noise is represented by cars, airplanes, alarms, external air-conditioning systems, people/tourists passing, the audience itself. When it's present, background noise is hardly avoided

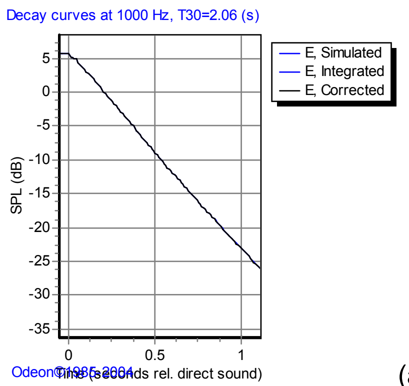
1.3 Visual factors

It is demonstrated that visual and auditory sensory systems have a cooperative interaction, and "the result of this synergy is an increase of the overall reaction speed of processing signals"[6]. This means that the visual aspect is crucial in listening to music, especially during live concerts. In big public squares, in stadium or even in big forums, for amplified concerts, the distance between the source and the receiver can be really high, up to 80-90 m. In this case what is source? Typically it's represented by some arrays of loudspeakers positioned besides the stage. And what does the receiver receive? He usually receives very "lo-fi" information: he/she can see very small figures (musicians) on the stage or bigger ones coming from some screen positioned on the top of the stage or somewhere else; and he/she listens to a strong direct sound accompanied by some late strong (and dangerous) reflections. This means that in principles there is a "strange" interaction between the visual and the acoustical information, which yields to listen to music in a very unusual way.

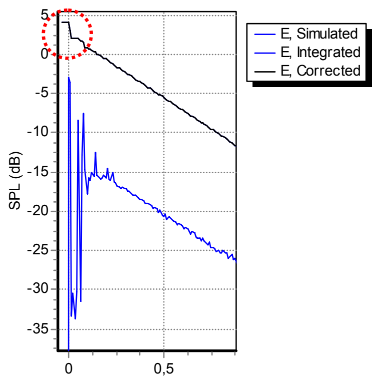
c)	***Concert hall / Auditorium***	***Public Square***
Max distance source – receiver	30 – 40 m	80 – 90 m
Viewing	The possibility of good viewing toward the stage area is almost always a prerequisite and every paying listener has his own seat	Audience is usually standing (usually no sloping audience is foreseen); the stage is usually somewhere over the heads of the audience
Delay: movements vs	For very large concert halls (more than 1500 seats) for audience far	For audience far from the stage a delay between the movements of the

sound	from the stage a delay between the movements of the musicians and the related sound can be perceived	musicians and the related sound, can be perceived
Lights	Lights are usually focused on the stage. This can give the sensation of higher level of sound	Lights are usually not only focused on the stage, but very often they are also present all over the square and in the adjacent streets, reducing the concentration of both audience and musicians

Table 1 (a,b,c) - Main differences in terms of geometrical, acoustical and visual factors, between closed spaces for music (concert halls) and open spaces (public squares)

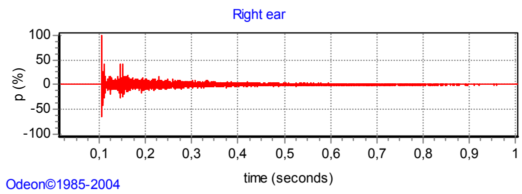


(a)

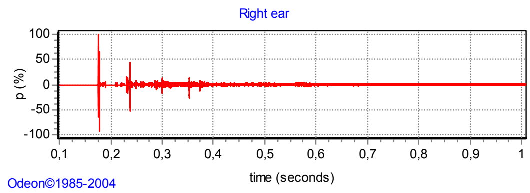


(b)

Figure 1 (a, b) – Typical decay curves for a concert hall (shoe-box shape) (a), and for a public square (b). In this last decay it's possible to see the "step" at the beginning (red dashed circle) which is caused by infrequent and intermittent early reflections

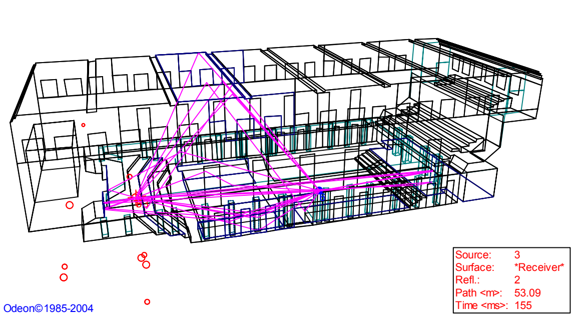


(a)



(b)

Figure 2 (a, b) – Typical impulse responses - only right ear - for a concert hall (shoe-box shape) (a) (early reflections, absence of echoes), and for a public square (b) (few early reflections, strong late reflections, possibility of echoes or even flutter echoes)



(a)

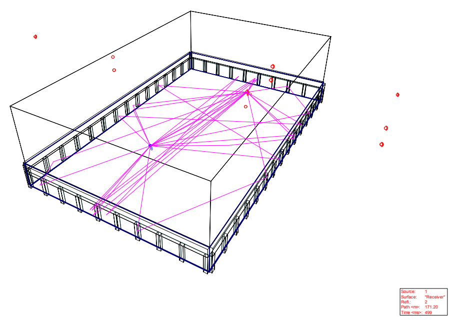

(b)

Figure 3 (a, b) – Typical 3D reflections paths for a concert hall (Musik Verrein) (a), and for a public square (b); this has almost only horizontal reflections (2D reverberation)


(a)

(b)

Figure 4 (a, b) – Audience area: differences between the audience area of an Opera House (in Prague (CZ)) and the ones in a public square (in Lugano (CH) – Estival Jazz) during a concert

2 CONSIDERATIONS

2.1 RT

Reverberation time (T30) seems not to be sufficient to understand the acoustical quality of an open space, because it does give enough information about the real sound decay: the same value of T30 can be the result of different types of decay. The initial step caused by the lack of early reflections is not "seen" by T30.
Also, T30 does not tell anything about the late part of the decay, which can be heard after the end of a song/speech, especially when there is a coupling or sagging decay.

2.2 C80

It was demonstrated that two different rooms (a concert hall and a roman theatre)[5] having the same RT can sound very different and this difference can be explained by the different values of C80, which means: what we really hear is something described also by the Clarity of sound rather than RT.
But if some echoes are also present, C80 is not always able to describe the sound of the place: C80 can be quite high just because some echoes are within the 0 – 80 ms interval.

2.3 STI

Other considerations can be made regarding the use of the Speech Transmission Index (STI). STI is a function of RT and background noise: usually, when measuring and simulating it, a very high SNR is chosen which is true only in those spaces where this important condition is respected (i.e. closed spaces with a low NC value). In public places during a performance or a speech, the SNR is not always high, because background noise can be very high due to people talking, car passing by, church bells and/or alarms ringing, air-conditioning system spreading noise outdoor, etc. This means that also STI, calculated or simulated has to take into account this factor. Decreasing of STI is to be expected passing from a high to a low SNR.

3 HOW IS IT POSSIBLE TO DETECT ECHOES?

The main problem when listening to music (in particular pop concerts, with very short notes) and/or someone speaking in an unroofed auditorium are the detecting of echoes or, even worse, flutter echoes.

3.1 Auralization

If a model is designed with a computer simulation program, auralization can be a good way to understand if late reflections can be heard as echoes[1], especially if the software can calculate the late reflections by a very accurate method[5]. In this way experiments demonstrate that echoes (and/or flutter echoes) are perceived depending of the type of music which is played in that particular virtual space:

- for 'short notes' (rock, jazz, funk music) and for speech, the following equation[2]

$$\Delta L \approx -0{,}6 \cdot t_0 - 8 \text{ [dB]}$$

gives the threshold of absolute perceptibility, and tells that if the delay (in milliseconds) between the direct and the first reflection is t_0, then the reflected sound is still audible as a distinct sound (echo) even when the difference $L_{direct} - L_{reflected}$ is ΔL. Of course echoes can be caused both by one strong reflection and by many reflections arriving in the same time interval.

- for 'long notes' music (classical, choir, etc.) the same formula is not always correct. Late reflections can be heard as a small increase in sound pressure, and can give some coloration (which can also increase the potentiality of some genres of music). In this cases, especially when the concert is not amplified, other parameters can be considered (see paragraph "Strength (G)").

In these and other cases, auralization can help to detect all the possible defects (echoes, flutter echoes, coloration due to periodic reflections and also delayed sound from lateral arcades[8]), in addition to all the parameters and formulas.

3.2 Centre Time (Ts)

Centre time, known also as the 'gravity time', is defined as:

$$T_s = \frac{\int_0^\infty t \cdot p^2(t) \cdot dt}{\int_0^\infty p^2(t) \cdot dt} \text{ [ms]}$$

A high value of Ts is usually (in closed spaces for music) an cue of low clarity, but in the case of open public places it may also indicate the presence of echoes and/or flutter echoes: in fact Ts is sensitive also to the late energy, which is mainly represented by possible echoes.
Values of 90-160 ms (especially at low-mid frequency)[3] are usually calculated for typical concert halls, while in the case of open spaces Ts can be 230-300 ms. The great "weight" that the energy associated to a late reflections (possible echoes) has, is able to "shift" the gravity centre of the impulse response to higher values.
Open places have acceptable values when receivers are close to the direct field, and it increases with distance from the source, where echoes are usually heard by means of auralization.

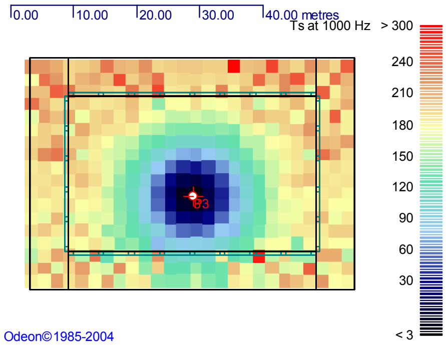


Figure 5 – Distribution of Centre Time (Ts) in a public square. High values (>230-300 ms) are observed from a certain distance from the source, in particular out of the direct field.

4 OTHER PARAMETERS

4.1 Strength (G)

Like in the case of concert halls, Strength can be used also in open spaces to know the level and the distribution of sound energy in the audience area, G being defined as:

$$G = 10 \cdot Log \left\{ \frac{\int_0^\infty [E(t)]^2}{\int_0^\infty [E_A(t)]^2} \right\} \text{[dB]}$$

where E_A is the impulse response measured with the same sound source in an anechoic room at 10m.

This is a good index for open spaces in case of non-amplified music, especially when problems of echoes are not so important, to realize if all the listeners are reached by music at proper levels.

5 CONCLUSIONS

Reverberation time (T30), as well as clarity of sound (C80) and speech transmission index (STI) are not always the most accurate parameters to evaluate the acoustics of an open public places, while Centre Time (Ts) and Strength (G), together with auralization, can be satisfactory because they tell more about the presence (or not) of echoes and flutter echoes (Ts and auralization), and about a proper distribution of sound energy into the audience area (G).

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7 ADKNOLEGDEMENTS

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