ASA 1994
Sabine Centennial Meeting
Cambridge, Ma
pp: 239-242

SOME NEW CONSIDERATIONS ON THE SUBJECTIVE IMPRESSION OF REVERBERANCE AND ITS CORRELATION WITH OBJECTIVE CRITERIA

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ABSTRACT

The room acoustics laboratory at Ircam, Paris, has undertaken a series of objective measurements as well as listening tests in different concert halls and opera houses throughout Europe.

Focusing on subjective reverberance, the relations between perceptual attributes and objective measures will be discussed. Especially addressed will be the ambiguity between the reverberation time, measured on the later part of the integrated impulse response, and the early decay time EDT, measured from the beginning of the integrated decay, in explaining the perceptual factor of reverberance. The importance of additional parameters such as the frequency dependence of the reverberation as well as the fine structure of the room impulse response will be discussed, recent studies at Ircam having underlined the importance of an intermediate packet of second reflections.

Furthermore, the influence of the type of music performed as well as the size and composition of the orchestra will be discussed.

1 INTRODUCTION

Since the times of Sabine [1] a number of acousticians, like Eyring or Kuttruff [2,3], have proposed alterations to his famous reverberation time formula. Furthermore, a number of ways how to best measure it in real rooms have been proposed. In most standards, nowadays, in order to gain independence of the importance of the direct sound as well as for the problem of background noise, the interval on which the decay slope is to be measured is fixed to [-5 dB, -35 dB].

But a number of acousticians have as well proposed different criteria. This includes Vilhelm Lassen Jordan, who proposed the measure of an *early decay time* (EDT) [4], to be evaluated over the first 10 dB of the integrated decay curve. The Göttingen group around Manfred Schroeder [5] proposed to enlarge the interval to the first 15 dB of the integrated decay, or to rather constrain the time interval and to evaluate the decay over the first 160 ms.

Another problem is how to determine the slope of the decay especially for the measurements of early decay times. Whereas Manfred Schroeder [6], when proposing his method of the integrated decay curve, used linear regression on the data points within the first 10 dB of the decay, David Griesinger [7] proposes to take the absolute time difference between the direct sound arrival time and the time t(-10 dB) re. steady state level (or -15 or -20 dB, when other definitions are used), multiplied by six to correspond to a 60 dB decay.

All of these criteria are supposed to explain the subjective correlate to reverberation, the “subjective reverberance”. We feel that the distinction between the objective measure of “reverberation time” and the perceptual attribute of “reverberance” should always be made clear.

2 THE MEASUREMENTS

A series of measurements and listening tests in nine European halls was carried out, including four concert halls, three operas and two auditoria. Impulse response measurements (using maximum length sequences) were made using a directive loudspeaker, but an "omnidirectional" loudspeaker could be reconstituted by summing the energetic contributions of the different emission directions. The reverberation time was calculated using linear regression, in an interval determined by the noise floor level but usually close to the [-5 dB, -35 dB] interval. This reverberation time will furthermore be called late reverberation time. Different early decay times were calculated from the integrated decay curves: EDT5, EDT10, EDT15, EDT20 and RT160, respectively evaluated over 5, 10, 15, 20 dB and 160 ms from the beginning of the integrated decay. We followed David Griesinger's proposal of taking the absolute difference rather than calculating a regression constant as we believe that this method is perceptually meaningful: it corresponds to six times the time interval it takes for a sound to decay from steady-state level to -10 dB below steady-state level.

Additionally, energy ratios for early to late energy were calculated for different time intervals of the early and late contributions. All of these measures were calculated in octave bands ranging from 63 Hz to 8 kHz.

Subjective listening tests were performed at exactly the same location as used for the measurements. Listeners (mostly acousticians and/or musicians) responded to a structured questionnaire while listening to a concert. One of the questions was asking for reverberance. The same questionnaire was used for concert halls, operas and auditoria.

Whereas for the measurements all halls were empty, for the listening tests all halls were fully occupied. Currently we are investigating the possibility of correcting the measurements to a fully occupied state by using computer modelling techniques developed at Ircam. First results look promising, but do not fundamentally change the interpretation of the relationships between reverberance and the different objective criteria of reverberation.

3 CORRESPONDANCE WITH OBJECTIVE CRITERIA

The first question is whether a single questionnaire and a constant scale can be applied to such different halls as concert halls and operas, where in each hall "typical" music, for the type of hall, was listened to. The correspondence of the average subjective judgments of reverberance for each hall with the mean late reverberation times of the halls is shown in figure 1a. The correspondence is quite good even across the different types of halls, but it has to be said that no concert halls with relatively short reverberation times of e.g. 1.7 seconds (unoccupied) were included in the tests. This would probably lead to judgments of reverberance clearly inferior to those of the operas with about 1.3 seconds. Correspondence is improved when using deviations from proposed "optimum" reverberation times for the different types of music (the values for optimum reverberation times are taken from [8]), figure 1b.

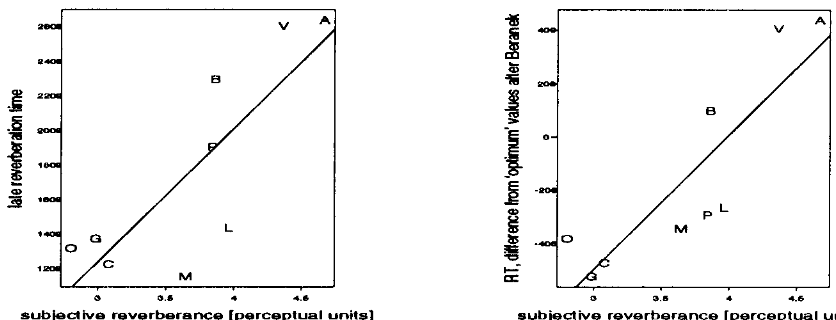

Figure 1: Subjective reverberance vs. objective late reverberation time, absolute values of unoccupied halls (left figure), *and deviation from optimum values for type of music, for operas (C,G,M), concert halls (A,B,P,V) and auditoria (L,O)*

But the improvement is moderate, correlation coefficients are $r = 0.81$ and $r = 0.87$, respectively. Rather than using deviations from questionable optimum reverberation times, for the rest of this paper it was decided to restrain the analysis to the concert halls.

Individual places will be considered for these halls as listeners noted considerable variations in the impression of subjective reverberance within a hall. Table 1 lists the correlation coefficients for several objective criteria and for several frequency bands for this case of individual places in the concert halls.

	125 Hz	250 Hz	500 Hz	1kHz	2kHz	4kHz	MEAN+0.5*ΔHF
late RT	0.002	0.337	0.464	0.527	0.562	0.431	0.595
EDT5	0.209	0.447	0.503	0.568	0.639	0.434	0.594
EDT10	0.166	0.469	0.519	0.579	0.644	0.460	0.628
EDT15	0.122	0.457	0.515	0.574	0.635	0.467	0.637
EDT20	0.094	0.441	0.510	0.569	0.625	0.469	0.639
RT160	0.271	0.517	0.540	0.607	0.661	0.442	0.632
O80/R80	-0.421	-0.458	-0.504	-0.563	-0.568	-0.401	-0.538
O80/R160	-0.358	-0.477	-0.513	-0.567	-0.617	-0.435	-0.586
O40/R40	-0.412	-0.473	-0.492	-0.574	-0.672	-0.477	-0.626
O40/R160	-0.416	-0.515	-0.520	-0.593	-0.682	-0.479	-0.649

Table1: Correlation coefficients r of several objective acoustical criteria with the notion of subjective reverberance, for 36 places in 4 concert halls. Three digits are given to facilitate comparison, they are not all significant. O... *indicates the early energy time interval, so* O80 *is the energy from 0 to 80 ms;* R... *indicates the late energy time interval, so* R80 *is the energy from 80 ms to infinity.*

What can be seen in table 1 is that correlation coefficients are optimal for the 2 kHz octave band. Several other proposals like the average of the reverberation times over a number of frequency bands or the maximum value of the reverberation time within a number of octave bands (which perceptually could make sense) were equally calculated, but consistently correlations remain optimal for just the 2 kHz band. Earlier laboratory experiments at Ircam [9] showed that for the notion of reverberance a confusion between global reverberation time and high-frequency reverberation time occurs. For those tests, the objective criterion best linked to the corresponding perceptual axis turned out to be a weighted sum of the reverberation time at mid-frequencies and the slope of the reverberation time towards high frequencies. So, as an alternative to taking the sole octave band around 2 kHz, a weighted sum of the average on the octave bands 250 Hz to 4 kHz and 0.5 times the slope from mid-frequencies (average of the 500 and 1k octave bands) towards high frequencies (average of the 2k and 4k octave bands) is proposed, leading to nearly identical correlation coefficients, cf. the last column of table 1.

The performance of EDT in explaining subjective reverberance is superior to that of the late reverberation time. This can be seen for the matrix of individual places in concert halls, cf. table 1, but it also consistently occurred for other considered ensembles of hall averages or individual places. A further advantage of EDT over RT is that it takes into account the directivity of the source. In the listening tests the Berlin Philharmonic hall was judged, for seats in front of the orchestra, as being less reverberant when listening to the first piano concerto by Brahms than when listening to other orchestral music. This is linked to the strong directivity of the piano, diminishing the importance of the late reverberation in the hall. A corresponding difference could be found when comparing EDT measurements for an omnidirectional loudspeaker and EDT measurements with a loudspeaker emitting towards the frontal direction.

Astonishing is the good performance of RT160, the reverberation time evaluated on the first 160 ms of the decay. This is a first indication that the very beginning of the impulse response is of major importance in the perception of reverberance.

The importance of the fine structure of the impulse response can be seen in an even stronger way when looking at the energy ratios between early and late energies, considering different time intervals for both of them. Correlations are optimal when constraining the early energy to the first 40 ms of the impulse response. Furthermore, correlations turn out to be optimal when taking the 40 first ms as the early energy and all the energy from 160 ms onwards as the late energy, completely neglecting the arriving energy in the time range 40 to 160 ms. In fact it even seems that energy arriving in this time interval tends to increase the impression of reverberance.

4 DISCUSSION

In the laboratory experiments carried out at Ircam using dissimilarity judgments, the results of which have only partly been published yet [9,10], consistently the early energy and the late energy showed up as perceptual factors. Optimising the relationships between objective criteria and the perceptual factors by considering the masking of parts of the impulse response, it turned out that in a lot of cases most of the energy between 40 ms and 160 ms is in fact masked by the preceding energy (direct sound plus first reflections). Neglecting the masking rules of when this energy still has to be considered, the early energy is hence close to O40 (the energy within the first 40 ms) and the late energy close to R160 (the energy from 160 ms onwards). As it is shown in a companion paper [11], in real halls the subjective notion of "loudness" of the hall is explained by the overall strength, i.e. more or less the sum of the early and late energy. It is hence not surprising to find the ratio of early to late sound as another primordial factor in explaining results of real hall tests.

But the laboratory experiments revealed an independent perceptual axis linked to EDT (or RT, once again the correlation with EDT15 being slightly superior) whenever the reverberation time was varied in the tests. In real halls the two objective parameters of EDT and early to late energy are of course always strongly correlated. So, when the ratio of early to late energy is interpreted as being linked to clarity, the high correlation coefficient with reverberance suggests that a confusion is taking place between the subjective notions of reverberance and clarity. Furthermore, the interdependence of envelopment and late reverberated energy is well known [12,13], it is hence not surprising to find a reciprocal influence of intermediate and mainly lateral reflections on the subjective impression of reverberance.

5 CONCLUSION

The above discussion leads us to put forward the following conclusion: there is an independent perceptual factor of reverberance that is linked to the early decay time, probably best EDT15 to incorporate variations of EDT within a hall as well as changes in late RT. But, when explaining the responses to the question of "reverberance" in a questionnaire, one additionally has to consider that subjects will inevitably be influenced by the related notions of "clarity" and "envelopment". It is up to interpretation whether one considers these substitution effects as intrinsic to the notion of reverberance or as a confusion with other perceptual factors. EDT15 can certainly be considered as a best compromise to explaining the effects of variations in late RT and variations of the early to late energy.

Additional tests are currently set up at Ircam using the *spatialisateur* in order to distinguish the influences of the different objective criteria. They will use double slopes of the decay that permit to at least partially decorrelate the objective parameters. Furthermore, the masking rules established in the laboratory as well as the correlations in real halls suggest that reverberated energy is more strongly perceived when moved back in time, a finding that could be very interesting for the design process of halls.

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