USE OF G AND C_{50} FOR CLASSROOM DESIGN

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1 INTRODUCTION

Reverberation time is an enduring and intuitive descriptor of the room acoustic response. It is used not only as a criterion for room conditions, but also commonly to infer the speech intelligibility and the ambient noise level resulting from a specific noise source. However, the acoustic configuration of typical classrooms, with the majority of the absorption concentrated on one surface, do not have an acoustic response that is well described by the reverberation time[1]; there is also a high level of uncertainty in the prediction of reverberation times in classrooms[1]. Reverberation time with classical theory is therefore not a good predictor of the qualities of classrooms in which we are interested, namely speech intelligibility and background noise from activities within the room.

Several researchers have returned to first principles recently to reconsider the requirements of the acoustic response in classrooms. Notably, to enable speech intelligibility, Bradley[2] has considered the requirements in terms of Signal to Noise Ratio (SNR), while Nijs and Rychtarikova[3] have considered the use of the parameter U_{50} to determine suitable reverberation times to enable good speech intelligibility with background noise.

An in depth investigation of acoustic conditions in classrooms of different acoustic response, coupled with users perception of those spaces, has been reported in the Essex Study[4]. The acoustic response of some of those rooms has been measured in more detail, and the results are presented in this paper. It is demonstrated that the acoustic response may be usefully understood in terms of Strength, G and Clarity, C_{50} ; the potential for these parameters to explain some of the results of the Essex Study is discussed. Appropriate values for Strength and Clarity are proposed for classrooms, and from these suitable ranges of reverberation times can be determined for different users and room sizes, to enable adequate SNR and Clarity.

2 BACKGROUND

Speech intelligibility is a function of background noise as well as room acoustic response; however, to specify suitable design parameters, it is convenient to separate these aspects of acoustic performance, to use separate descriptors for room acoustic response and for background noise.

The parameters Speech Clarity, C_{50} and Strength, G, have been proposed as measures of the quality of the acoustic response with which we are concerned in classrooms. These are defined in ISO 3382-1[5]; however, the descriptions are valid for a particular source and a particular receiver position, such that spatial averaging is not defined or meaningful in those situations. If used to describe a particular room, then additional description of the spatial application is required.
This paper proposes a definition of G and C_{50} to describe classroom conditions, and describes the measurement of these in the rooms used for the Essex Study.

Sabine's classical theory for reverberation time involves the implicit concept that the decay of sound is exponential; while this assumption may be valid in relatively lightly damped and well diffused spaces, it is not so true in well damped or non-diffused rooms. In this case, the relationship between reverberation time and other acoustic descriptors that rely on the exponential decay will also break down.

The present work seeks to determine if Strength, G and Clarity, C_{50} may be more usefully and practically employed to describe the qualities in which we are interested. Previous work[6] has suggested that spatially averaged measurements at a distance greater than the mean free path (mfp) may be suitable. In this paper, the minimum proximity between speaker and measurement positions is taken as half the square root of the floor area, d/2, where $d = \sqrt{S}$., for spatially averaged values.

3 THEORY

3.1 Spatial variation of Strength

According to Barron's revised theory[7], with modifications proposed by Sato and Bradley[8], the diffuse sound level is a function of distance *d* and may be given by:

$$Diff_{bar} = \frac{4(1-\alpha)^{fb.d/mfp}}{A} \quad \textbf{(1)}$$

Where:
α is the average absorption coefficient
A is the equivalent sound absorption area
mfp is the mean free path
fb is a weighting factor

The direct sound level is expressed as:

$$Dir = \frac{Q}{4\pi d^2} \quad \textbf{(2)}$$

Where:
Q is the directivity of the source (Q = 1 hereafter)
d is the distance between the source and the receiver

The factor *fb* has been introduced by Sato and Bradley[8] and a value of 2 has been proposed in furnished rooms. A value of fb = 1.5 matches better with these and previous measurements by Apex[6], and is used in the ensuing discussion.

The total sound level at a distance d is given by Eqn (3).

$$L_{p,bar} = L_w + 10\log(Dir + Diff_{bar}) \quad \textbf{(3)}$$

From this we can calculate the Strength, G from its definition in ISO 3382-1:

$$G = L_p - L_{p,10m} \quad \textbf{(4)}$$

Where $L_{p,10m}$ is the level in free field at 10 m. It can also be expressed as:

$$G = L_p - L_w + 31 \quad \textbf{(5)}$$

Substituting eqn (5) into eqn (3) gives the value of G as a function of distance:

$$G = 31 + 10\log(Dir + Diff_{bar}) \quad \textbf{(6)}$$

3.2 Spatial variation of Clarity

Clarity is defined as the ratio of early to late arriving sound, with the distinction for speech made at 50 ms between early and late. From ISO 3382-1:

$$C_{50} = L_{p,early} - L_{p,late} \quad \textbf{(7)}$$

Using Barron's revised theory from Eqn (3) and integrating to 50 ms:

$$L_{p,early} = L_{w,sp} + 10\log\left(Dir + Diff_{bar}.\left(1 - e^{\frac{-0.69}{RT}}\right)\right) \quad \textbf{(8)}$$

$$L_{p,late} = L_{w,sp} + 10\log\left(Diff_{bar}.e^{\frac{-0.69}{RT}}\right) \quad \textbf{(9)}$$

Where $L_{w,sp}$ is the sound power level of speech.
These expressions can be simplified if we limit our interest to distances well away from the source, so that direct sound is not significant, and in rooms where the Strength is not much below G = 15 dB, to:

$$C_{50} = 10\log\left(\frac{1 - e^{-0.69/RT}}{e^{-0.69/RT}}\right) \quad \textbf{(10)}$$

4 CORRELATING STRENGTH AND CLARITY WITH SPEECH INTELLIGIBILITY

4.1 Voice level, SNR and intelligibility

In re-evaluating the requirements for classrooms, Bradley[2] has determined Signal to Noise ratios (SNR) that are required for different types of students. He concludes that a value of 20 dB SNR is necessary for primary school age students, and that 15 dB is sufficient for secondary school pupils.

Teacher voice levels may vary considerably in classrooms, and the requirement for teachers to raise their voices causes them problems. According to Pelegrin-Garcia and Bruskog[9], the reverberation time mouth-to-ears, or the sensation of reverberance for the speaker, is lower than the measured reverberation time. Thus, to provide good acoustic conditions for both listeners and speakers, the Strength should be sufficient, although this is mostly a problem only in large rooms. Qualitative evidence from the Essex study shows that some teachers take time to become accustomed to the less reverberant rooms. For the purposes of this assessment, therefore, the possibility for a room to support speech at normal levels is considered, and the typical value of 60 dB(A) at 1 m is used, disregarding directivity effects.

Where the background noise level is 35 dB(A), a signal level of 55 dB(A) is required to achieve 20 dB SNR, although Nijs and Rychtarikova include noise from the pupils in the background level. For a signal of 60 dB at 1 m, the value at 10 m in the freefield is 40 dB; hence the required value of room Strength is G = 15 dB to achieve a signal level of 55 dB(A) at the back of the room.
From this analysis, it may be considered that for lower levels of Strength between source and receiver positions, within a background noise environment of 35 dB(A), a talker would need to raise their voice to provide sufficient signal, and the room could be considered overdamped.

4.2 Clarity and STI

The correlation between Speech Transmission Index, STI, and Clarity, C_{50}, is discussed by many researchers, notably Marshall[10]. Marshall has indicated the weighting factors in Table 1 for the relevant octave band measurements to best correlate C_{50} with STI.

Octave band	**500 Hz**	**1 kHz**	**2 kHz**	**4 kHz**
Weighting factor	0.15	0.25	0.35	0.25

Table 1: Intelligibility weighting factors to correlate C50 with STI, from Marshall

Marshall has also indicated the C_{50} weighted values that correlate with different levels of STI as shown in Table 2.

Weighted C_{50} dB	**-6**	**-3**	**0**	**3**	**6**	**9**
STI	0.3	0.4	0.5	0.6	0.7	0.8
Category	Poor	Fair		Good		Excellent

Table 2: Marshall's correlation for C_{50} and STI

From this it is suggested that a minimum acceptable value of 3 dB for C50 is required for classroom design, although higher values would be preferred, at the most adverse location in the room.

5 DESIGN PARAMETERS

The variation of the Strength and Clarity with room size and reverberation offers useful insight into classroom conditions. Consider a square room of floor area S, such that the length of one side is $= \sqrt{S}$. This is the longest distance likely between a teacher and listener if the teacher stands in front of the class in the middle of one side, and thus describes the worst conditions within the room. Considering a constant room height of 3 m, we can investigate the relationship between the reverberation time, floor area, Strength and Clarity.

Firstly, the spatial variation of Clarity with distance is plotted using equations (7), (8), and (9). As noted previously, at distances well away from the source, Clarity is not a significant function of distance, but only of reverberation time. Figure 2 illustrates the spatial variation of Clarity for a reverberation time of 0.65 seconds at a distance *d* from the source in each room.

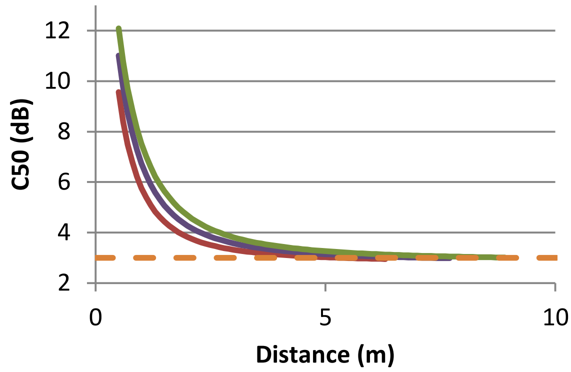

Figure 1: Variation of C_{50} with distance in different room sizes with constant RT = 0.65 s according to Eqns (7), (8), and (9). Red, purple and green curves are for S = 40 m^2, 60 m^2, and 80 m^2 respectively. Orange dotted line denotes C_{50} = 3 dB

For the distance between talker and listener to be $d = \sqrt{S}$ as described above, the relation between reverberation time and Clarity is irrespective of room size as shown in Figure 2. Figure 2 shows that to achieve a value for C_{50} of 3 dB, a maximum RT of 0.65 seconds is permissible in an occupied room; other pertinent points are also marked.

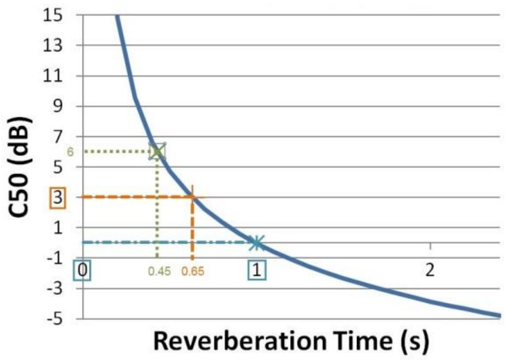

Figure 2: Clarity as a function of RT at maximum listener distance

Now, to achieve a particular level of Strength, such as G = 15 dB in this example, the minimum reverberation time is a function of room area is shown in Figure 2, when the listener is at the back of the room a distance *d* from the speaker.

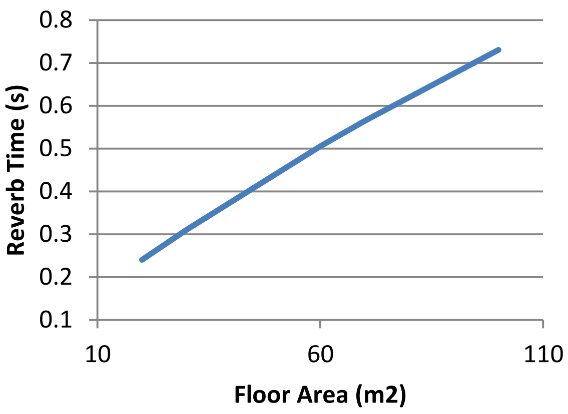

Figure 3: Minimum RT against floor area to achieve a value of Strength, G = 15 dB at distance d

Consideration of the maximum reverberation time to maintain the Clarity and minimum reverberation time to achieve signal Strength leads to the preferred design range of reverberation times for various room sizes, as shaded green in Figure 4.

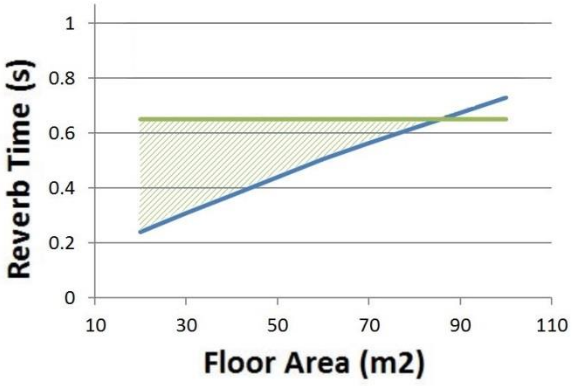

Figure 4: Design range (green hatch) to maintain a Strength of G ≥ 15 dB and Clarity ≥ 3 dB

Figure 4 illustrates that according to this description, it is not possible to design a room larger than about 85 m^2 with a 3 m ceiling height and enable Good speech intelligibility for a listener at the back of the room without the talker raising their voice, when the background noise is 35 dB(A). These conditions also correlate with experience.

This method allows rooms to be designed for speech intelligibility based on the room dimensions, reverberation time, background noise level, teacher vocal effort and the SNR required for the occupants.

6 MEASUREMENTS

Measurements have been undertaken in four class rooms at Sweyne Park School. The spatial variation of G and C_{50} was investigated in a room with a nominal RT of 0.4 seconds across the frequency range.

6.1 Measured spatial variation of Strength

The results of the spatial variation measured are shown in Figure 5 for the mean value of the mid-frequency 500 Hz, 1 kHz and 2 kHz octave bands, denoted G_{mf}.

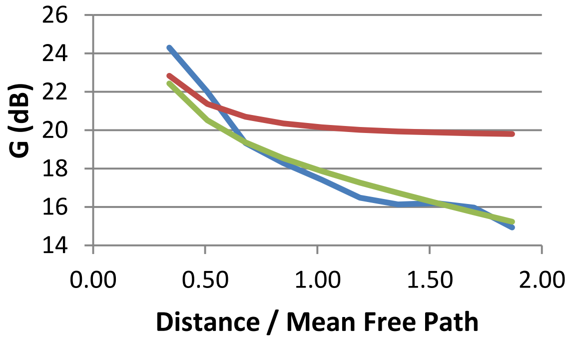

Figure 5: Spatial variation of G_{mf} as a function of distance / mfp, with fb = 1.5 from Eqn. (6) shown in green. Blue curve is measured values; red curve shows G with simple classical theory

Figure 5 illustrates how classical Sabine theory over-estimates the sound level in this classroom by up to 7 dB. Experience in other rooms[5] shows similar differences, and illustrates how simple classical theory does not explain the acoustic response of this type of room.

6.2 Results of spatial variation of Clarity

The average results for three lines of spatial decay and the four octave bands 500 Hz – 4 kHz with Marshall's intelligibility weighting factors[10] are shown in Figure 6.

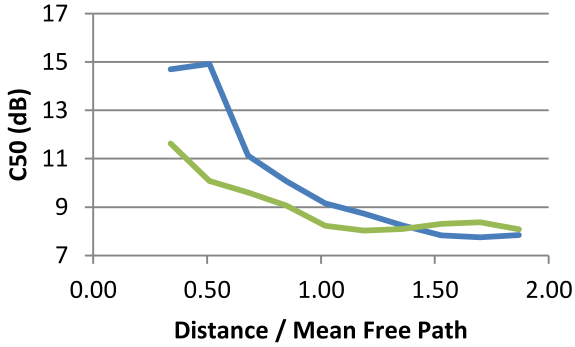

Figure 6: Spatial variation of C_{50} as a function of distance / mfp, with fb = 1.5 from Eqn. (7), (8), and (9), shown in green. The measured values are shown in blue

Figure 6 illustrates that although the Clarity is measured to be considerably higher than that predicted from the theory presented at closer proximity between source and receiver, towards the back of the room there is good agreement.

6.3 Spatially averaged results

A series of measurements were made in four classrooms, beyond a distance of d/2 where $d = \sqrt{S}$, and the results arithmetically averaged. In Figure 7 below, the measured values of Strength are compared with the calculated values, themselves based on the measured reverberation time. The calculated values are based on a distance of 0.75d, approximately the mean distance over which the measurements were made.
The nominal mid-frequency reverberation times of the four rooms, measured as a T20 and averaged between 500 Hz and 2 kHz as required by English regulations, is shown in Table 3 below.

Room	**MA1**	**MA3**	**MA2**	**MA5**
T_{mf} / secs	0.36	0.42	0.92	1.18
Floor area / m^2	47	46	53	52

Table 3: Mid-frequency reverberation times

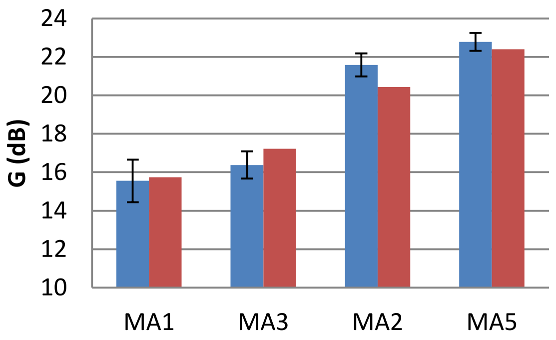

Figure 7: Comparison of measured (blue) and calculated (red) results for G from the measured reverberation time.

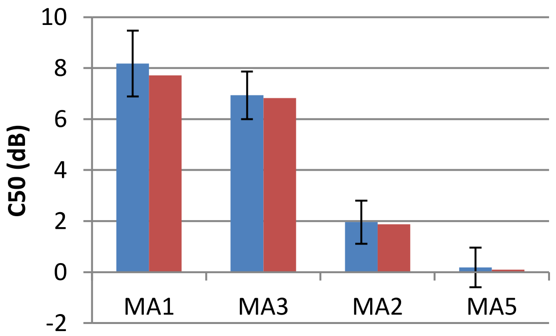

Figure 8: Comparison of measured (blue) and calculated (red) results for C_{50} from the measured reverberation time.

Two aspects of the measurements are noteworthy: firstly, the calculated results averaged over half of the room correlate well with the measured results for both parameters. Secondly, the standard deviation in the measurement of Clarity is relatively high. It is suggested that the values for G and C_{50} may be defined and measured as being beyond a distance of d/2, where $d = \sqrt{S}$ to characterize the room.

7 DISCUSSION OF ESSEX STUDY RESULTS

One of the most striking results of the Essex Study was the revelation that background noise, measured as the L_{A90}, decreased much more significantly with decreasing reverberation time than can be explained with a simple constant sound power source model with sound pressure levels described by the reverberation time and classical theory. Strength also represents the sound pressure level from other sources of noise within the room, as well as the teacher, and hence it may be considered as the most relevant parameter to describe background noise levels. Considering noise from the other side of the room, which effectively forms the background noise, the calculated Strength according to Eqn (6) can be plotted against room reverberation time, as shown in Figure 9.

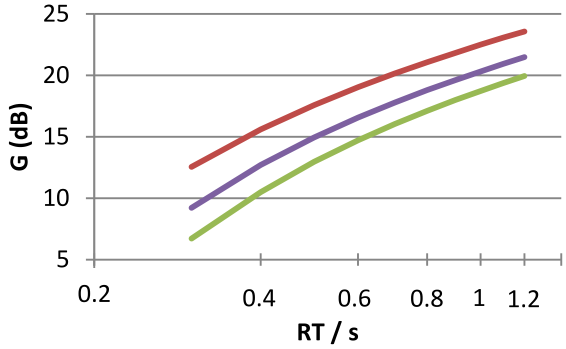

Figure 9: Strength at distance *d* as a function of reverberation time, plotted on a log scale. Red, purple and green curves for S = 40 m^2, 60 m^2 and 80 m^2 respectively.

The results above illustrate that there is a non-linear relationship between Strength, with the spatial definition adopted here, and the log of the reverberation time. A classical model disregarding Barron's revised theory would have a straight line relation between reverberation time on a log scale and Strength, with a change of 3 dB for doubling the reverberation time. This graph illustrates that in a 60 m^2 room, the change in Strength when changing the reverberation time from 0.8 to 0.4 seconds is 6 dB. The factor *fb* being greater than 1.0 increases the slope of the lines, and also the curvature at lower reverberation times. The model presented here may help explain some of the results in the Essex Study reproduced in Figure 10 with the kind permission of the authors.

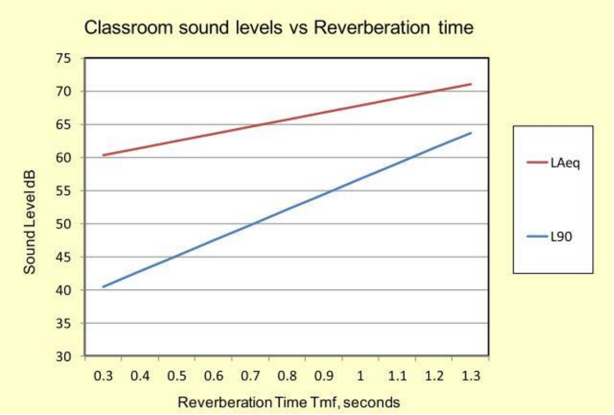

Figure 10: Ambient and background noise with reverberation time from the Essex Study

As is noted in the Essex Study, there may be a change of behaviour associated with a dampening of noise levels, in the manner of the Lombard effect – as ambient or background chatter noise levels reduce, so pupils reduce the noise level they produce.

It is worth noting that none of the rooms measured at Sweyne Park have a value of G less than 15 dB, despite the very low reverberation times, due to the size of the rooms. Hence the potential effect of over-damping, and subsequent requirement for a teacher to raise their voice, is not tested in these rooms. The consistent preference reported in the Essex Study of all respondents for the most damped rooms remains the most compelling evidence for those acoustic conditions.

8 CONCLUSION AND FURTHER WORK

Reverberation time itself can be a poor descriptor of the relevant acoustic conditions in classrooms. However, more recent models of the behaviour of sound in well damped or poorly diffused rooms that are based on reverberation time can help understand how Strength and Clarity may be more useful to describe speech intelligibility. Nonetheless, the design parameters should be Strength and Clarity rather than the reverberation time which may be inferred from the models presented in this paper.

The two aspects of classroom acoustic response that are considered here for speech intelligibility are SNR and speech Clarity. There is a conflict for the room response to optimise both these qualities, with a higher SNR achieved with more reverberant conditions, but consequently less Clarity. The effect of the Strength on background noise levels revealed so dramatically by the Essex Study is a strong argument for classrooms to have the lowest possible Strength that enables sufficient SNR; in this way the highest Clarity will be achieved.

The necessary conditions to achieve good speech intelligibility for primary age children are both SNR $\geq$ 20 dB and Clarity $\geq$ 3 dB, or higher. Lower values of SNR may be acceptable for older children or more adept listeners. From the appropriate SNR, the minimum value for Strength may be determined. It may be appropriate to use the same four octave band weighting factors for Strength as used for Clarity by Marshall. These suggest that the range adopted for English regulations, between 500 Hz and 2 kHz is too limited.

In larger rooms, or higher background noise level conditions, Strength and Clarity may be used as design parameters to determine the acoustic conditions required.

9 ACKNOWLEDGEMENT

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