Optimizing Classroom Acoustics Using Computer Model Studies

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Abstract

Speech intelligibility in rooms is determined by both room acoustics characteristics as well as speech-to-noise ratios. These two types of effects are combined in measures such as useful-to-detrimental sound ratios which are directly related to speech intelligibility. This paper reports investigations of optimum acoustical conditions for classrooms using the ODEON room acoustics computer model. By determining conditions that relate to maximum useful-to-detrimental sound ratios, optimum conditions for speech are determined. The results show that an optimum mid-frequency reverberation time for a classroom is approximately 0.5 s, but speech intelligibility is not very sensitive to small deviations from this optimum. Speech intelligibility is influenced more strongly by ambient noise levels. The optimum location of sound absorbing material was found to be on the upper parts of the walls.

Résumé

L'intelligibilité de la parole dans une chambre est déterminée par les caractérsitiques acoustiques et aussi par les rapports parole-bruit. Ces deux types d'effets sont combinés dans des mesures comme des rapports son-utile/son-nuisible, qui sont reliés directement à l'intelligibilité de la parole. Cet article présente les investigations des conditions acoustiques optimums pour des classes en utilisant le modèle généré par la programme acoustique ODEON. En déterminant les conditions reliées aux rapports son-utile/son-nuisible maximums, il est possible de trouver des conditions optimums pour la parole. Les résultats montrent qu'un temps de réverberation mi-fréquence optimum pour une classe est environ 0.5 s, mais l'intélligibilité de la parole n'est pas très susceptible aux petites déviations de cet optimum. L'intélligibilité de la parole est influencée plus fortement par les niveaux de bruit ambiant. On trouve que la location optimum de matériel absorbant est sur la partie supérieure des murs.

1.0 Introduction

The intelligibility of speech in a classroom must be critical to the learning process. When the words of the teacher or of other students are not completely intelligible, students cannot learn efficiently. Speech intelligibility (SI) can be measured as the percentage of test words heard correctly by groups of listeners. Intelligibility can also be related to various acoustical quantities, which can then be used to assess conditions for speech in rooms without having to perform cumbersome speech intelligibility tests.

The intelligibility of speech in rooms is related to the levels of the speech sounds and ambient noises as well as to the room acoustics characteristics of the space. The higher the level of the speech sounds relative to the ambient noise, the greater the intelligibility of the speech. Thus, the effects of speech and noise levels are usually considered in terms of speech-to noise ratios (S/N), (i.e. a signal-to-noise ratio where the signal is the speech). Speech intelligibility increases with increasing speech-to-noise ratio until an S/N of approximately +15 dB is reached which typically corresponds to 100% SI [1,2].

Speech intelligibility is also influenced by room acoustics. This was originally assessed in terms of the reverberation time (RT) of the room. Various optimum reverberation times have been recommended to maximize speech intelligibility in rooms and these optimum values usually increase with increasing room volume [3]. The effect of room acoustics on speech intelligibility is now thought to be better related to measures that more correctly assess the benefits of both the direct sound and reflections arriving within about 50 ms after the direct sound [1,4,5]. Because our hearing system effectively integrates these early reflections together with the direct sound, they contribute to increasing intelligibility. However, later arriving reflections degrade intelligibility by causing one word to blur into the next. Thus, early-to-late arriving sound ratios are now thought to be better indicators of the effect of room acoustics on speech intelligibility. For example, C_{50} is the ratio of the early-arriving speech energy in the first 50 ms after the direct sound to the later-arriving speech energy.

Three different acoustical measures are available that combine both the room acoustics and speech/noise aspects into a single quantity. The speech transmission index (*STI*) (or its simplification *RASTI*) is perhaps the best known [6]. It is derived from modulation transfer functions that are influenced by both ambient noise and room acoustics. The useful-to-detrimental sound ratio concept was first proposed by Lochner and Burger [5] and a simplification was later evaluated by Bradley [1,4]. In this ratio, the useful energy is the early arriving speech sound. The detrimental energy is the sum of the late arriving speech energy and the ambient noise. The third measure, *%Alcons,* is derived from the direct sound level, the ambient noise level and the reverberation time [7]. All three measures have recently been compared and shown to be strongly correlated with each other [12].

The current paper reports on investigations to determine how to obtain optimum acoustical conditions in a typical classroom. The classroom was modeled using the ODEON room acoustics ray tracing program. Acoustical conditions were assessed in terms of both early-to-late arriving sound ratios (C_{50}) and useful-to-detrimental sound ratios (U_{50}). It was possible to determine optimum reverberation times for a typical classroom and also the optimum placement of sound absorbing material to maximize speech intelligibility.

2.0 The ODEON Model Classroom

The ODEON room acoustics ray-tracing program (version 2.6 for DOS) was used to model a typical classroom. The geometry of the classroom is illustrated in Figure 1. The room was 11 m long by 9 m wide and 3.4 m high with a volume of 336.6 m^3. The students were simulated by an absorbing block 1.8 m from the rear wall 3 m from the front wall and centered between the side walls. As shown in Figure 1, one source position was used and 9 receiver positions. Four different sources were used alternatively at the same location. One source was omni-directional and the others had the directionality of a human talker. One of the 3 directional sources was directed down the centre line of the classroom towards the rear wall. The other two were directed at ±45 degrees from this.

Material	α	δ
Concrete (floor)	0.02	0.1
Gypsum Board (walls)	0.04	0.5
Students	0.69	0.7
Ceiling tile	0.95	0.1
Ceiling tile (half absorption)	0.47	0.1

Table 1. Material properties, absorption coefficient α and diffusion coefficients δ.

For simplicity, in this paper only 1000 Hz results will be presented. The 1000 Hz absorption coefficients of the various surfaces are given in Table 1. The table also shows the diffusion coefficients for each surface used in the ODEON calculations. The floor was assumed to be a smooth hard concrete surface and the walls gypsum board. The block representing the students was given the absorption coefficients of people sitting on wooden chairs.

In the initial experiments the absorption of the ceiling was varied but in the final experiments absorption representative of highly absorbing ceiling tiles (shown in Table 1) was used.

3.0 Acoustical Measures

The ODEON program directly calculates values of the reverberation time (*RT*) and the early decay time (*EDT*). It also calculates expected sound pressure levels (*SPL*) based on the source having a sound power representative of speech. Although ODEON does not provide C_{50} values, it does provide values of Deutlikeit (*D*) which is usually referred to as 'definition' or 'distinctness' in English. Deutlikeit measures the ratio of early-arriving to total speech energy and can be related to C_{50} as follows,

$$C_{50}(ODEON) = 10\ \log[D/(1-D)],\ dB \qquad (1)$$

Using this equation, C_{50} values were calculated from the ODEON output of *D* values.

For an ideal exponential decay, one can calculate C_{50} values from decay times. From the ratio of the integrals of the early (0 to 50 ms) and the late (50 ms to ∞) intervals of an ideal exponential decay one obtains,

$$C_{50}(RT) = 10\ \log[e^{(13.815*0.05/RT)} - 1],\ dB \qquad (2)$$

in terms of reverberation time (*RT*) or,

$$C_{50}(EDT) = 10\ \log[e^{(13.815*0.05/EDT)} - 1],\ dB \qquad (3)$$

in terms of the early decay time (*EDT*).

Equations (2) and (3) provide simple techniques for estimating C_{50} values when only the decay times are

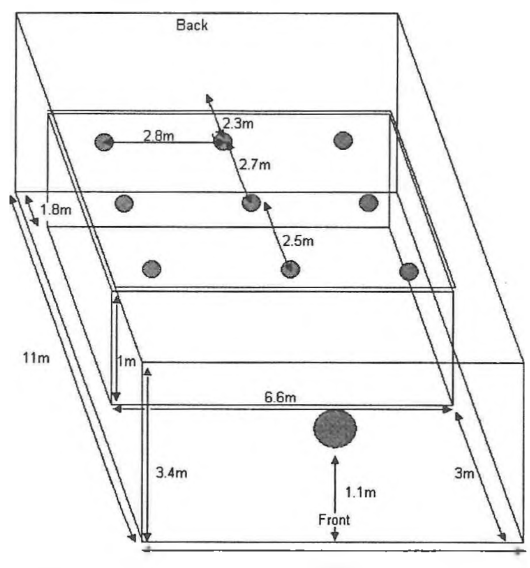

Figure 1. ODEON model of the classroom showing source position (large filled circle) and receiver positions (small filled circles).

known. Because they are based on the assumption of ideal exponential decays, they will give different C_{50} values than those calculated from the actual impulse responses but may be satisfactory approximations in small rooms.

Useful-to-detrimental ratios are the ratio of the early arriving speech energy to the sum of the late arriving speech energy and the ambient noise. They relate directly to speech intelligibility and can also be derived from C_{50} values combined with speech and noise levels as follows,

$$U_{50} = 10\log\{c_{50}/[1+(c_{50}+1)\,10^{(Noise-SPL)/10}]\},\ dB \quad (4)$$

where c_{50} are the linear and not the logarithmic early-to-late ratios.

4.0 Comparisons with Predictions from Sabine and Eyring Equations

The ODEON calculations were first validated by comparing calculated *RT* values with those obtained from the Sabine and Eyring reverberation time equations. Because it is not obvious what values of diffusion coefficients should be assigned to each surface, these comparisons give a check that the results appear to be reasonable. In these tests the 1000 Hz absorption coefficient of the ceiling was varied from 0.1 to 0.9 in steps of 0.2. This gave a realistic range of acoustical conditions in the classroom for comparisons of the calculated reverberation times.

Figure 2 compares the resulting reverberation times from ODEON ray tracing results and from the Sabine and Eyring reverberation time equations. All 3 results show decreasing reverberation times with increased ceiling absorption as would be expected. The ODEON calculations of *RT* agree very closely with those obtained using the Sabine equation. *RT* values obtained using the Eyring equation are a little lower. The results suggest that the ODEON model is a reasonable representation of a typical classroom.

C_{50} values obtained from ODEON ray tracing results ($C_{50}(ODEON)$) were compared to estimates using equations (2) and (3) above to test the accuracy of these approximate estimates of C_{50} values. These are compared in Figure 3 for the same variations of ceiling absorption. Increased ceiling absorption leads to less later arriving sound energy and to increased C_{50} values. For these cases, both estimates of C_{50} values agree reasonably well with the ODEON calculations. However, C_{50} values estimated from *EDT* values agree best with the C_{50} values calculated directly from ODEON impulse responses. *EDT* values are more influenced by the details of early reflections and hence can be used to better estimate C_{50} values. $C_{50}(RT)$ values were least satisfactory for the $\alpha = 0.9$ case where the *RT* was most different to the *EDT*.

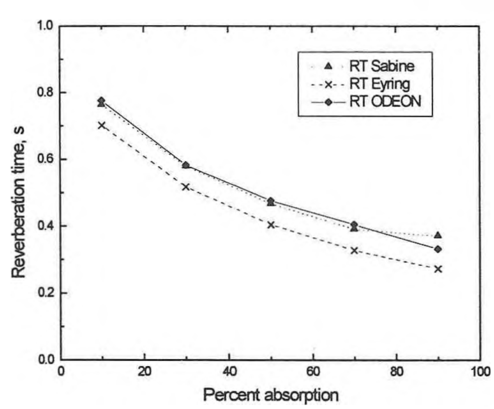

Figure 2. Reverberation time versus ceiling absorption for average of 9 receivers and OMNI source at 1000 Hz.

5.0 Estimating the Optimum Reverberation Time

For the results in the previous section, adding more absorption to the ceiling systematically decreased the reverberation time. At the same time C_{50} values increased, indicating better conditions for speech. However, the addition of absorption to the ceiling also caused a decrease of calculated speech sound levels in the classroom. For a particular ambient noise level, this would lead to decreased speech-to-noise ratios and hence decreased speech intelligibility. Thus, adding absorption has both beneficial and detrimental effects. Increased absorption leads to both increased C_{50} values and decreased speech-to-noise ratios. There must be some intermediate amount of absorption that would lead to an optimum compromise corresponding to the maximum speech intelligibility. This optimum amount of sound absorbing material will relate to a particular reverberation time, which will be the optimum reverberation time for maximum speech intelligibility in the classroom.

This optimum reverberation time can be determined from the condition that leads to the maximum useful-to-detrimental sound ratio (U_{50}). U_{50} is directly related to

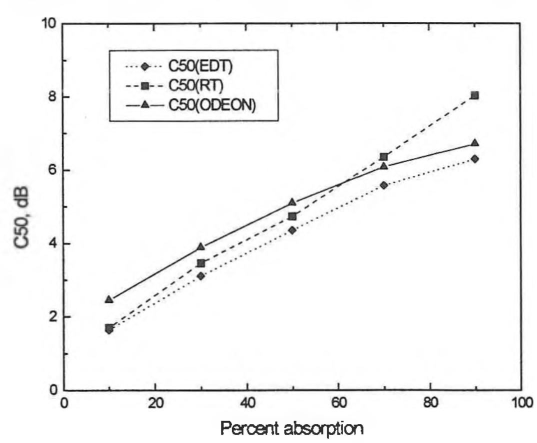

Figure 3. C_{50} versus ceiling absorption for average of 4 sources and 9 receivers, 1000 Hz.

speech intelligibility and combines both the influence of room acoustics (C_{50}) and speech-to-noise ratio. Thus, the condition that leads to the maximum U_{50} value will correspond to the maximum speech intelligibility and to the optimum combination of C_{50} and speech-to-noise ratio. The reverberation time corresponding to this optimum condition is the required optimum reverberation time for speech in the classroom.

The same 5 different absorption coefficients for the ceiling were used as in the previous section, varying from 0.1 to 0.9 in steps of 0.2. These led to 1000 Hz reverberation times of from approximately 0.3 to 0.8 s and the range of C_{50} values shown in Figure 3. Using the speech levels calculated by the ODEON program and background noise levels of 35, 40, 45, and 50 dBA, U_{50} values were calculated. This gave a wide but realistic range of both room acoustics and speech-to-noise conditions. The resulting U_{50} values are plotted in Figure 4. For the 'reasonably good' case of a 40 dBA ambient noise level, the maximum U_{50} value corresponds to a 0.48 s reverberation time. However, the optimum reverberation time varies somewhat with the ambient noise level. For noisier conditions more reverberant conditions help increase speech levels and hence improve speech-to-noise ratios. For quieter ambient noise situations, less reverberant conditions lead to maximum U_{50} values because they correspond to improved room acoustics conditions (i.e. increased C_{50}).

One can estimate speech intelligibility scores from U_{50} values [8] using the following equation,

$$SI = 98.24 + 0.861\,(U_{50}) - 0.0863\,(U_{50})^2,\ \% \quad (5)$$

This gives the expected intelligibility on a simple rhyme test where 97% or higher corresponds to excellent conditions for speech. For the 40 dBA ambient noise level case, speech intelligibility scores were estimated from the U_{50} values and are plotted in Figure 5. Although the optimum speech intelligibility corresponds to the case of approximately 0.5 s reverberation time, a wide range of reverberation times lead to speech intelligibility scores within 0.5% of the maximum. Thus, obtaining exactly the optimum reverberation time is not very critical to achieving near optimum conditions for speech. This is partly because intelligibility is directly related to C_{50} but only indirectly related to RT.

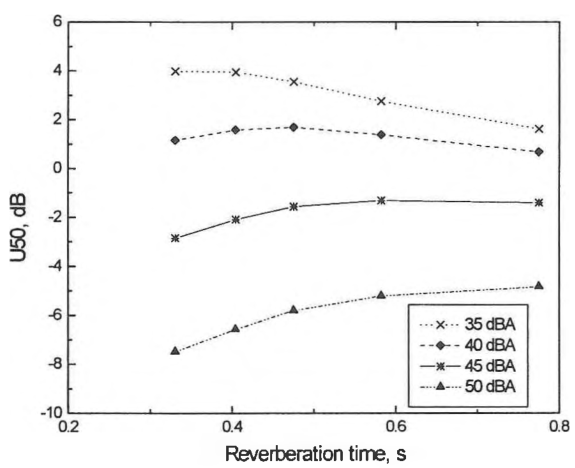

Figure 4. U_{50} versus ceiling absorption, OMNI source, 1000 Hz.

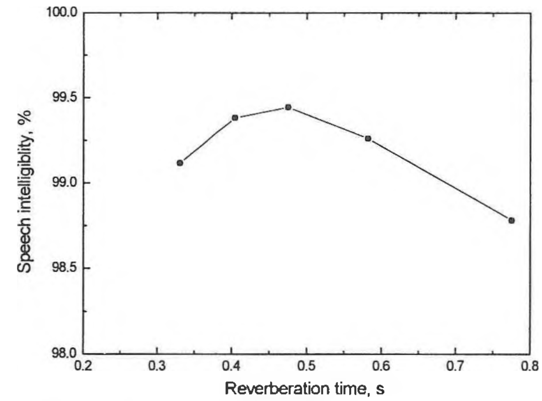

Figure 5. Variation of speech intelligibility with reverberation time for 40 dBA ambient noise.

6.0 Optimum Placement of Sound Absorbing Material

Although the reverberation time is only influenced by the average sound absorption in the room, C_{50} values can be affected by the location of the absorbing material. Thus it may be possible to improve conditions for speech by more optimally locating the available sound absorbing material and without changing the reverberation time. Previous recommendations include: putting absorption on the ceiling and rear wall [9], and avoiding treating the centre of the ceiling with sound absorbing material [10]. In fact a German standard [11] recommends this latter approach for rooms such as classrooms.

While it is difficult to change the location of absorption in a real room, it can be done quite conveniently in a computer model such as ODEON. Nine different configurations of added sound absorbing material were tested. In all cases the total sound absorption was kept constant. A highly absorbing ceiling material was assumed to have an absorption coefficient of 0.95. The base case consisted of completely covering the ceiling with material having half this absorption coefficient (i.e. α=0.47). (This is essentially the same as the optimum reverberation time case for which the ceiling was 50% absorptive). Other cases consisted of covering an area equal to half the area of the ceiling with material with an absorption coefficient of α=0.95. The 9 absorption configurations are described in Table 3. The surface diffusion coefficients were as described in Table 1. All untreated areas of the walls and ceiling were gypsum board with properties described in Table 1.

#	Description
1	Full ceiling, α = 0.47
2	Front half ceiling, α = 0.95
3	Rear half ceiling, α = 0.95
4	Rear part ceiling and back wall, α = 0.95
5	Ring on ceiling and upper walls, α = 0.95
6	Ring on ceiling, α = 0.95
7	Ring on upper walls, α = 0.95
8	Upper side and rear walls, α = 0.95
9	Upper side walls, α = 0.95

Table 3. Description of 9 absorption configurations.

The location of the absorbing material was expected to influence conditions for speech by changing C_{50} values. The C_{50} values obtained at the nine receiver positions illustrated in Figure 1 were averaged and these mean values are plotted for each of the nine absorption configurations in Figure 6. Mean C_{50} values are given for each of the 4 different sound sources described in section 2 above. The results in Figure 6 indicate small differences between the different sources but the same variations occur among the 9 absorption configurations for all sources. For example, the omni-directional source tends to produce C_{50} values that are a fraction of a decibel lower than the other sources but there are variations of up to 4 dB among the various absorption configurations.

The clarity in the room is maximum when there is an absorptive material on the upper parts of the side and rear walls (condition # 8), and results are almost identical when the absorptive treatment is continued to the upper part of the front wall. The most inferior treatment is when the absorption is limited to the front half of the ceiling (i.e. over

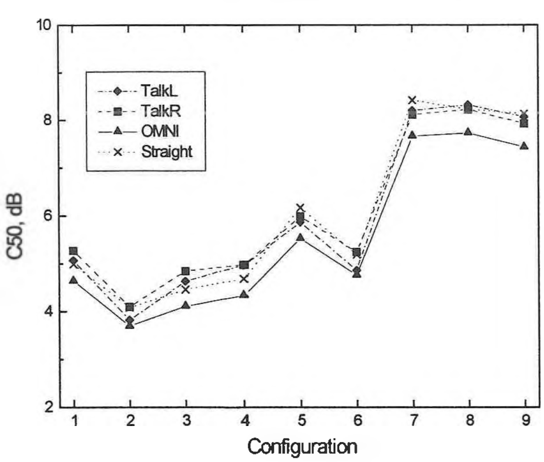

Figure 6. Mean C_{50} for each absorption configuration and source type, 1000 Hz.

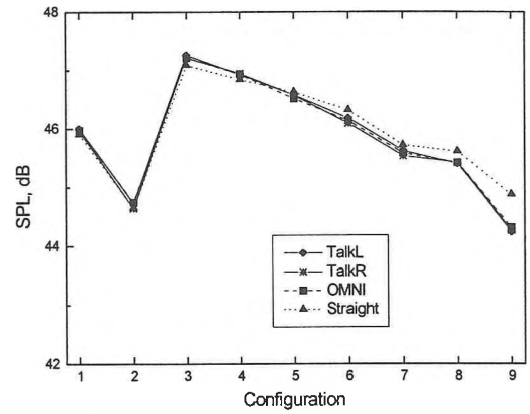

Figure 7. Mean speech sound pressure level (SPL) for each absorption configuration and source type, 1000 Hz.

the source). Treating the rear part of the ceiling and the rear wall (condition 4) was not optimum as recommended by one previous study [9].

Although conditions # 7 and # 8 lead to maximum C_{50} values, they did not optimise speech sound levels. The corresponding 1000 Hz mean speech sound levels are shown in Figure 7 for the 9 configurations and for all 4 sources. The source type has less effect on sound levels than the small effects on C_{50} values. Varying the location of the sound absorbing material has a maximum effect on speech sound levels of just under 3 dB. Treating only the rear half of the ceiling (condition # 3) leads to the maximum speech sound level. Conditions # 7 and # 8 that corresponded to maximum C_{50} values have sound levels about 1.5 dB lower than the maximum found for condition # 3. Thus, again there is a trade-off between increasing clarity (C_{50}) and increasing speech levels.

The condition that optimizes both C_{50} and speech-to-noise ratios can be determined by finding the configuration that corresponds to the maximum useful-to-detrimental ratio

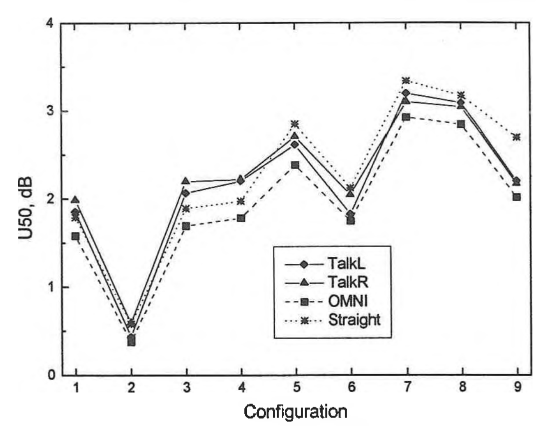

Figure 8. Mean U_{50} for each absorption configuration and source type, 40 dBA ambient noise level, 1000 Hz.

(U_{50}). Using an ambient noise level of 40 dBA, U_{50} values were calculated for each configuration and for each source type. These U_{50} values are shown in Figure 8. Again source type has only a small effect but U_{50} values increase by about 1.3 dB from configuration # 1 (full ceiling treated) to configuration # 7 (upper part of walls treated).

7.0 Conclusions

By varying the absorption coefficient of the classroom ceiling, it was possible to derive an optimum reverberation time of approximately 0.5 s. This corresponds to the maximum useful-to-detrimental sound ratio (U_{50}) and hence to the maximum speech intelligibility. Although this corresponds to the maximum speech intelligibility, a range of reverberation times lead to almost the same speech intelligibility. Speech intelligibility is within 0.5% of maximum within the range from at least 0.3 to 0.6 s reverberation tme. Thus it is not important to achieve exactly the optimum 0.5 s reverberation time. The results in Figure 4 show that ambient noise level is a much more important determinant of U_{50} values and hence speech intelligibility in a classroom. Further, the optimum reverberation time also depends on the ambient noise level and a little more reverberant conditions are helpful in higher noise levels.

The location of added sound absorbing material has different effects on speech clarity (C_{50}) and speech sound level. Maximum speech clarity (C_{50}) was obtained with the absorptive treatment on the upper parts of the side and rear walls. Conditions with improved speech clarity (C_{50}) tended to have reduced speech sound levels. However, when considering the combined effects in terms of useful-to-detrimental sound ratios (U_{50}), the configuration with the upper parts of the walls treated produced optimum results. Thus the most effective location of sound absorbing material is to add it to the upper parts of the walls and to add an amount sufficient to produce an occupied 1000 Hz reverberation time of approximately 0.5 s.

The determination of optimum reverberation time and the optimum location of the added sound absorbing material is also influenced by the ambient noise level. However, the location of the absorbing material on the upper parts of the walls would still be appropriate in noisier conditions and so can be more generally recommended. Because these treatments all involved the same total amount of sound absorbing material, there should be little difference in the cost of the various configurations. Thus, the optimum configuration represents an acoustical improvement with no extra cost.

This is an initial exploratory study that demonstrates that there are possible modest improvements to classroom acoustics. These would correspond to quite small improvements in speech intelligibility but their subjective importance is not known. Further work is required to assess the subjective importance of these changes and to explore the effects of other parameters. Further studies should include the effects of other room shapes and other possible configurations of absorptive treatments. One could also consider different amounts of added sound absorbing material and include results for a range of frequencies. Future studies should also consider the effect of added absorption on ambient noise levels. The present studies are based on the useful-to-detrimental sound ratio concept and hence incorporate the trade-off between room acoustics and speech-to-noise ratios included in that measure. New studies could repeat this process in terms of speech transmission index (*STI*) values to verify that the same conditions are found to be optimum. Finally, the process should be validated by measurements in actual rooms with varied absorption configurations.

The use of computer models such as ODEON is seen to be a convenient method for determining the importance of parameters influencing speech intelligibility in rooms. The combination of such computer model studies and a limited number of validation measurements in real rooms is a cost-effective approach for developing better information for designing better classrooms. The resulting improvements in speech intelligibility could translate to more relaxed and accurate communication between students and teachers.

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