PREDICTION AND IMPROVEMENT OF THE CONVERSATION INTELLIGIBILITY IN DINING SPACES

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1. INTRODUCTION

A recent survey in some college dining halls shows that the speech communication between diners is generally poor [1]. The problem is especially serious during the formal halls. Diners complained that they must raise voices because of noise disturbance from other talkers but the intelligibility was still poor. In many restaurants and other dining spaces a similar problem also exists [1-2].

A closely related topic is the acoustic problem at cocktail parties, which has been paid attention for a number of years [3-7]. Previous works are of importance for the understanding of acoustic phenomenon in cocktail parties and dining halls. However, less attention has been paid to the prediction and improvement of acoustic quality, particularly in terms of architectural design. From the viewpoint of space use, useful design guidelines have been given for dining halls, such as for table size and seat spacing [8]. However, it is often the case that a dining hall is satisfactory from the viewpoint of space use, but the acoustic quality is rather poor.

The objective of this research is to study the basic characteristics of conversation intelligibility in dining halls, and to investigate the effectiveness of strategic architectural acoustic treatments on improving the intelligibility. Based on the radiosity techniques, a computer model, RADD, has been developed for calculating the acoustic indices in dining halls. Using the model a parametric study has been carried out.

2. MODEL

The radiosity method is an effective technique for considering boundary diffusion. It has been used in room acoustics since the 1980's [9-13]. In RADD all the boundaries are treated as diffusely reflective according to the Lambert cosine law. If most parts of, or a large proportion of the energy incident upon, a boundary are diffusely reflective, which is the situation in many dining halls [1], due to the effect of multiple reflections, the sound field should still be close to that resulting from diffusely reflecting boundaries [13-14]. Moreover, there seems to be strong evidence that even untreated boundaries produce diffuse reflections [15]. This may further extend the application range of the model.

The model divides every boundary into a number of patches. The patches and receivers are used as nodes in a network and the sound propagation is simulated using the energy exchange between these nodes [16]. Energy response can be obtained for receivers at any location, from which the acoustic indices relating to dining halls can be determined, including the early decay time (EDT), reverberation time (RT), steady-state sound pressure level (SPL) and speech transmission index (STI).

The signal to noise (S/N) ratio is vital for the speech intelligibility. A significant feature of dining halls is that, for a given listener, the sound from the talker(s) in his/her conversation group (e.g. a dining table) is regarded as signal, and the sound from the other talkers is regarded as ambient noise. In RADD the sound power level of each talker can be given in a form of a single value or a spectrum [17-18]. The signal level is calculated by considering the directionality of the talker, the direct sound and the reflections from the table and room boundaries. As to the ambient noise from other talkers, the SPL from a talker to a listener is determined with the consideration of the talker's directionality, the direct sound, extra attenuation over the seat area due to grazing incidence, and boundary reflections. The seat attenuation is simplified as proportional to the talker-listener distance, expressed as E (dB/m) [19-21]. The directionality of takers is only considered in the near field: the far field sources are taken as omni-directional since the SPL is dominated by multiple reflections. In addition to the ambient noise from other talkers, general background sounds, from music, ventilation and a kitchen for example, may also affect the S/N ratio. In RADD this effect can be considered.

In RADD the reverberation caused by a given talker can be calculated at any seat position. For conversation intelligibility, the reverberation at a seat position caused by the talker in his/her conversation group is of particular importance. Most attention is paid to the EDT since it has been demonstrated that the early decay of a room governs the intelligibility [17-18,22].

The conversation intelligibility in RADD is measured using the STI, and its simplified version, the rapid speech transmission index (RASTI). Based on the survey [1], a relationship between calculated RASTI and the subjective rating of conversation intelligibility has been established for dining halls, as shown in Figure 1. The results suggest that the RASTI is an appropriate index for evaluating the intelligibility of dining halls, and that people will accept lower intelligibility in dining halls than in other spaces like underground stations [23]. In Figure 1 a relationship between the RASTI and dining enjoyment is also shown, again based on the survey.

For a given room condition, the model can give the maximum number of seats according to the requirement in intelligibility.

RADD was validated in an actual dining hall. The length, width and height of the hall were 10.5m, 10m, and 3.7m, respectively. The boundaries were fairly hard, and during the measurements there were 72 diners. At 500-1kHz the calculated RT was 1.58s, which was close to the measured value, 1.46s.

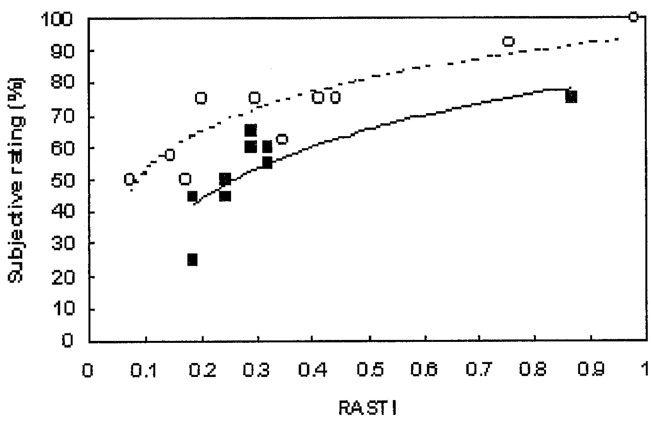

Figure. 1. *Relationship between the RASTI and subjective rating in six dining halls. The symbols are the survey results (O: conversation quality, with 0 as very poor, 25 as poor, 50 as average, 75 as good and 100 as very good;* n*: dining enjoyment, with 0 as very annoying, 25 as annoying, 50 as indifferent, 75 as*

enjoyable and 100 as very enjoyable). The curves are logarithmic regressions of the results (······, conversation quality, r=0.91; ——, dining enjoyment, r=0.85).

3. COMPUTATION

Using RADD a parametric study has been carried out in a number of hypothetical dining halls. The parameters studied include boundary absorption, absorber arrangement, seat density and arrangement, hall size, ceiling height and length/width ratio. For convenience the calculation is based on a single frequency.

3.1 Boundary absorption

Figure 2 illustrates an idealised dining hall design used for the analysis. The length, width and height of the hall are 10m, 10m and 3.5m, respectively. There are 100 seats with, using the architectural design guidelines minimum density [8], an average area per diner of 1 m^2. The table size is 0.8m by 1.2m and there are four diners per table. The height of the diners' head is 1.2m. It is assumed that all the talkers have the same source power level, which is set as 0dB. The source directionality is considered according to the conventional diagram at middle frequencies. The extra attenuation over the seat area is approximated as E=1dB/m [21]. To study the disturbance between diners, it is assumed that the ambient noise at a listener is only from other diners.

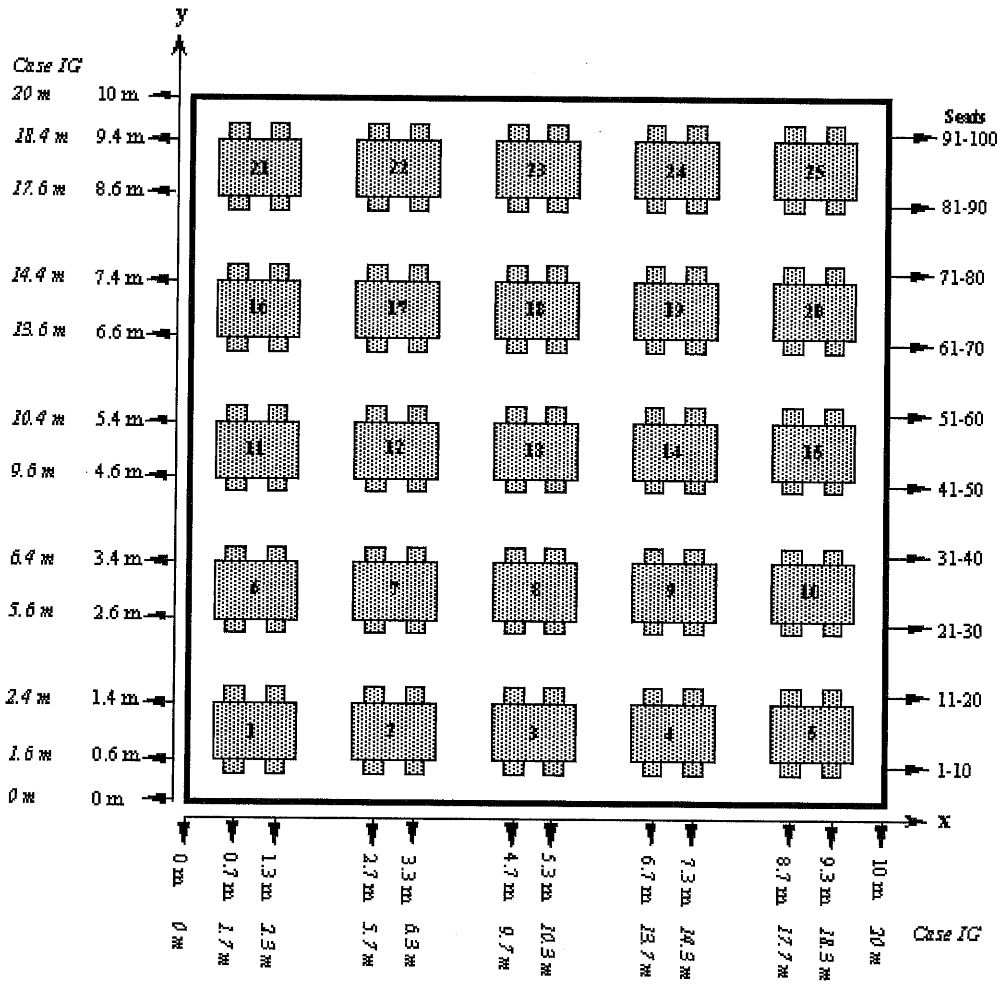

Figure 2. *Plan view of a typical dining hall (Cases I to V) of 10m by 10m by 3.5m, showing the table and seat numbers. The dimensions for Case IG (20m by 20m by 3.5m) are also given.*

The absorption coefficient of a wall or the ceiling is assumed to be uniform over the entire surface. Three absorption coefficients, 0.05, 0.5 and 1, are considered. For the dining area, two absorption coefficients, 0.2 and 0.7, are used [1]. The air absorption is considered as 0.002N/m.

Based on these conditions, a calculation is made in five cases with different boundary absorption coefficients: (1) Case I: dining area 0.2, walls and ceiling 0.05; (2) Case II: dining area 0.7, walls and ceiling 0.05; (3) Case III: dining area 0.2, walls and ceiling 0.5; (4) Case IV: dining area 0.7, walls and ceiling 0.5; and (5) Case V: walls and ceiling 1. Cases I and II represent typical situations without any sound absorbent treatment. Cases III and IV consider the absorbent treatment on the ceiling and walls. Case V is the outdoor situation, which gives the maximum effectiveness of absorbent treatments.

For the STI, a comparison between the five cases is made for dining table 7, a typical position in the hall (see Figure 2). Table 1 shows the EDT caused by a talker at seat 23, the SPL from the talkers of other tables, and the STI. The data in Table 1 are based on the average of the acoustic indices at seats 24, 33 and 34, namely, the other three diners in table 7. It is assumed that for this dining table there is only one talker. Two talker-listener distances, 0.8m and 0.3m, are considered. The former represents the common talker-listener distance, while the latter assumes that the listeners move much closer to the talker in order to improve the intelligibility. For each talker-listener distance, ambient noise from other tables is considered with one and two talkers per table.

Table 1. *Acoustic indices of dining table 7 in Cases I to V.*

Indices Cases	**I**	**II**	**III**	**IV**	**V**
EDT (s) by a talker at seat 23	1.53	0.53	0.29	0.2	-
SPL (dB) from talkers of other tables, 2 talkers/table	6.99	1.94	-0.31	-2.44	-7.2
STI, 2 talkers/table, talker-listener 0.8m	0.04	0.23	0.34	0.42	0.6
STI, 2 talkers/table, talker-listener 0.3m	0.24	0.48	0.59	0.67	0.88
STI, 1 talker/table, talker-listener 0.8m	0.1	0.33	0.43	0.51	0.7
STI, 1 talker/table, talker-listener 0.3m	0.31	0.55	0.66	0.74	0.98

For Cases I and II, from Table 1 it can be seen that with the common talker-listener distance, 0.8m, the STI is 0.1-0.33 with one talker per table and 0.04-0.23 with two talkers per table, which is generally unacceptable [17-18]. The poor intelligibility is mainly caused by the low S/N ratio, which is about –3 to -11dB. When the talker-listener distance is reduced to 0.3m, the STI increases to 0.31-0.55 with one talker per table, and to 0.24-0.48 with two talkers per table. With this range of STI the sentence intelligibility is generally over 80%.

The effectiveness of boundary absorption on improving the STI can be seen in Table 1. In comparison with Cases I and II, in Cases III and IV the EDT is about 60-80% shorter, the ambient noise level is about 4-8dB lower and consequently the STI is improved significantly. With a talker-listener distance of 0.8m and two talkers per table, for example, the STI increases from 0.04 in Case I to 0.34 in Case III, and from 0.23 in Case II to 0.42 in Case IV. Correspondingly, the sentence intelligibility in Cases III and IV is over 98%. Using more absorbers can further increase the STI. In Case V the STI is over 0.6, which indicates the maximum effectiveness of the absorbent treatment.

3.2 Seat density and hall size

To investigate the effectiveness of reducing seat density, calculation is made with Case IG, which corresponds to Case I, but the floor area is extended to 20m by 20m from 10m by 10m. Accordingly, the average area per diner becomes 4m^2. In Figure 2 the seating arrangement in Case IG is also illustrated.

The acoustic indices in Case IG are shown in Table 2. From Tables 1 and 2 it can be seen that in comparison with Case I, in Case IG the EDT is slightly (14%) lower and the S/N ratio is significantly (6.1dB) higher. Consequently, the STI in Case IG is considerably greater than that in Case I, by about 0.13-0.17. This demonstrates the effectiveness of increasing seat density on improving the conversation intelligibility.

Table 2. *Acoustic indices with enlarged area per diner (Case IG), raised ceiling height (Cases IH and IIIH) and increased length/width ratio (Cases IL and IVL).*

Indices / **Cases**	**IG**	**IH**	**IIIH**	**IL**	**IVL**
EDT (s) by a talker at seat 23	1.31	2.33	0.34	1.25	0.18
SPL (dB) from talkers of other tables, 2 talkers/table	0.9	7.44	-1.2	7.07	-5.1
STI, 2 talkers/table, talker-listener 0.8m	0.19	0.02	0.36	0.04	0.5
STI, 2 talkers/table, talker-listener 0.3m	0.4	0.18	0.6	0.26	0.74
STI, 1 talker/table, talker-listener 0.8m	0.27	0.06	0.45	0.11	0.59
STI, 1 talker/table, talker-listener 0.3m	0.44	0.25	0.66	0.33	0.81

By comparing Cases III and IG, two different methods of improving the intelligibility in Case I, it is apparent that increasing absorption is more efficient than enlarging the area per diner. Moreover, in most cases the former method is relatively less expensive and has a less effect on the space use. Furthermore, under a more absorbent room condition the early arrivals tend to talk quietly and thus later arrivals will not cause voices to be raised to shouting level. Consequently, the noise level can be reduced and the dining hall is less annoying to diners.

It is interesting to note that in Case IG if the seat number is increased to 400, the STI is not higher or even slightly lower, than that in Case I. This suggests that if the seat density is constant, the intelligibility between different hall sizes may not be significant. An important reason for this is that with increasing hall size, the decrease in S/N ratio caused by more talkers is approximately compensated by the increase in total absorption.

3.3 Ceiling height

If the ceiling height is increased, assuming that the absorption coefficient of each boundary is constant, reverberation time will become longer because the increase in volume is proportionally greater than that in absorption. Clearly, this has a negative effect on the intelligibility. However, the ambient noise level from other diners may become lower due to the increase in total absorption, and this has a positive effect on the intelligibility.

To investigate the overall effect, calculation is made with Cases IH and IIIH, which increase the ceiling height from 3.5m to 7m in Cases I and III, respectively. The acoustic indices in Cases IH and IIIH are shown in Table 2. By comparing Cases I and IH, where the wall absorption coefficient is 0.05, it can be seen that with a higher ceiling the EDT is considerably longer, by about 50%, the ambient noise level is slightly higher, by about 1.5dB, and consequently, the STI becomes lower. For example, with one talker per table and a talker-listener distance of 0.3m, the STI decreases from 0.31 in Case I to 0.25 in Case IH. When the wall absorption coefficient is 0.5, it is interesting to note that the opposite phenomenon occurs. By comparing Cases III and IIIH it can be seen that with a higher ceiling, although the EDT is still about 20% longer, the ambient noise level is about 1dB lower. As a result, in Case IIIH the STI is generally higher than that in Case III. Overall, these results demonstrate that when the ceiling height is increased, the STI becomes lower if the walls are acoustically hard, and can be higher when the walls are more absorbent. Clearly, the STI increase is more significant if the wall absorption is relatively strong in comparison with other boundaries.

For a flat dining hall, such as Case IG, with a raised ceiling the increase in reverberation is more significant than the decrease in the ambient noise level. This is because with increasing floor/height ratio, the wall absorption becomes relatively less important. As a result, the STI is likely to be diminished if the ceiling height is increased.

3.4 Length/width ratio

To investigate the effect of room shape, calculation is made with Cases IL and IVL, which correspond to Cases I and IV respectively, but the length/width ratio is changed to 4 from 1, so the floor area becomes 20m by 5m.

For dining table 8, a typical position in the hall, the acoustic indices in Cases IL and IVL are shown in Table 2, where the EDT and STI correspond to a talker at seat 23 and three listeners at seats 24, 28 and 29. Again, it is assumed that for this dining table there is only one talker. By comparing Tables 1 and 2, it can be seen that with a greater length/width ratio, the EDT is consistently about 10-20% shorter. This is probably because in the decay curve the initial energy is increased due to the reduced distance between a pair of walls. With respect to the ambient noise from diners, the difference between Cases I and IL is unnoticeable, while in Case IVL the SPL is almost 3dB lower than that in Case IV. An important reason for this is that with absorbent boundaries the sound attenuation along the length becomes significant [23-24] and thus, the disturbance from the diners in the far field becomes much less. Overall, with a given floor area, the conversation intelligibility can be improved by increasing the length/width ratio, and the improvement is more significant under a more absorbent room condition. From Case I to IL the increase in the STI is less than 0.02, whereas from Case IV to IVL, the STI increase is over 0.07.

3.5 Absorber arrangement

For a given amount of absorption, it is useful to investigate the effectiveness of strategic arrangement of the absorbers. For Case I, by increasing the average absorption coefficient from 0.09 to 0.25, four absorber arrangements are compared: (1) Case Ia: dining area 0.2, walls 0.05, ceiling 0.6; (2) Case Ib: dining area 0.2, walls 0.443, ceiling 0.05; (3) Case Ic: dining area 0.2, two opposite walls 0.836, other walls and ceiling 0.05; and (4) Case Id: dining area 0.75, walls and ceiling 0.5. A comparison between various absorber arrangements is shown in Table 3. The calculation configuration corresponds to that in Table 1. Only the situation with two talkers per table is considered. From Table 3 it can be seen that the variation between Cases 1 a to d is 0.02s in the EDT and 0.8dB in the SPL. Correspondingly, the variation in the STI is only 0.02.

Table 3. *Comparison of the acoustic indices between various absorber arrangements. The calculation is based on two talkers per table.*

Indices Cases	**Ia**	**Ib**	**Ic**	**Id**	**IGa**	**IGb**	**IGd**
EDT (s) by a talker at seat 23	0.44	0.46	0.44	0.44	0.41	0.49	0.41
SPL (dB) from talkers of other tables	2.15	1.9	1.93	1.35	-5.56	-4.7	-6.36
STI, talker-listener 0.8m	0.24	0.24	0.24	0.26	0.47	0.44	0.49
STI, talker-listener 0.3m	0.49	0.49	0.5	0.51	0.66	0.63	0.68

To investigate the effectiveness of absorber arrangements with a different room shape, calculation is made based on Case IG, namely a flat room. By increasing the average boundary absorption coefficient from 0.11 to 0.31, three absorber arrangements are compared: (1) Case IGa: dining area 0.2, walls 0.05, ceiling 0.6; (2) Case IGb: dining area 0.2, walls 0.836, ceiling 0.05; and (3) Case IGd: dining area 0.75, walls and ceiling 0.05. The results are shown in Table 3. When comparing Cases IGa and IGd with Case IGb, it can be seen that the EDT is shorter, the S/N ratio is greater and, consequently, the STI is considerably higher, by about 0.03-0.05. This means that with a given amount of absorption, it is better to arrange the absorbers on the ceiling or floor. An important reason for this effect is that in a flat room, the reflections between floor and ceiling dominate the sound field. In long rooms, it has been shown that the STI is the highest if the absorbers are arranged on one boundary in cross-section.

These results suggest that for a given amount of absorption, in a regularly-shaped dining hall, the difference in intelligibility between various absorber arrangements is negligible, whereas in a flat or long dining hall, it is important to strategically arrange the absorbers. A possible reason for the difference between regularly- and irregularly- shaped rooms is that in the former the sound energy at a receiver depends on many different patterns of sound path and thus, it is less efficient to strategically arrange the absorbers.

4. CONCLUSIONS

A computer model has been developed to calculate the acoustic indices of dining halls. Using the model, a parametric study has been carried out to study the basic characteristics of conversation intelligibility in dining halls, and to investigate the effectiveness of strategic architectural acoustic treatments on improving the intelligibility.

Computation using a typical dining hall design shows that a design merely based on the current guidelines for space use may lead to very poor conversation intelligibility. Increasing boundary absorption can typically increase the STI by 0.2-0.4, which is significant. For a given amount of absorption, in a regularly-shaped dining hall the difference in intelligibility between various absorber arrangements is negligible, whereas in a flat or long dining hall, it is important to strategically arrange the absorbers.

The intelligibility can also be improved by reducing seat density. If the area per diner is enlarged from $1m^2$ to $4m^2$, the increase in the STI is typically 0.13-0.17. With a constant seat density, the difference in the STI between different hall sizes is not significant. When increasing the ceiling height, the STI becomes lower if the walls are acoustically hard, and can be higher when the walls are more absorbent. For a given floor area, if the boundaries are absorbent, the intelligibility can be improved by increasing the length/width ratio. When this ratio is increased from 1 to 4, the STI improvement is typically over 0.07.

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