Empirical Prediction Of The Effect Of Classroom Design On Verbal-Communication Quality

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ABSTRACT

This study used empirical prediction models to investigate how verbal-communication quality in 'small', 'medium' and 'large' classrooms varies with classroom design, and identified the optimal designs. Verbal-communication quality was quantified by the room-average speech intelligibility. The design parameters studied were the occupancy, the unoccupied background-noise level, and whether or not the rooms were carpeted, had ceiling and/or wall absorption, or upholstered seats. The design parameters were varied, and the following quantities calculated: average classroom surface-absorption coefficient at 1 kHz, 1-kHz early-decay time, A-weighted background-noise level, and A-weighted speech-signal to background-noise level difference. The conditions under which optimal verbal-communication quality occurred were identified. Quality did not vary with absorption or early-decay time in any systematic way. High background noise, combined with either high absorption or low early-decay time, can lead to very low verbal-communication quality. Quality was low for negative values of signal-to-noise level, but increased quickly for higher values. In the 'small' and 'medium' classrooms, the optimal verbal-communication quality occurred with carpeting and absorption, and with un-upholstered seats. In the 'large' classroom, the optimal quality occurred with carpeting, absorption and upholstered seats. The most significant design factor in determining the verbal-communication quality of the rooms was the background noise.

RÉSUMÉ

A l'aide de modèles prévisionnels empiriques, l'influence de la conception de la salle sur la qualité de communication verbale est étudiée dans le cas d'une 'petite', une 'moyenne' et une 'grande' salle de classe, et les critères de conception optimale sont identifiés. La qualité de communication verbale a été quantifiée au moyen de l'intelligibilité verbale moyenne. Les paramètres de conception étudiés ont été le nombre d'occupants, le niveau de bruit de fond dans la salle non-occupée, et si, oui ou non, la salle était équipée d'un tapis, de matériau absorbant sur les murs et/ou le plafond, ou de sièges absorbants. Ces paramètres ont été variés et les quantités suivantes ont été calculées: le coefficient moyen d'absorption des surfaces à 1 kHz; le temps de décroissance initiale à 1 kHz; le niveau de bruit de fond pondéré A; le rapport signal-bruit pondéré A. Les conditions donnant une qualité de communication verbale optimale ont été identifiées. La qualité ne varie pas de façon systématique avec l'absorption ou le temps de décroissance initiale. Des niveaux élevés de bruit de fond, associés soit à une absorption élevée ou à un faible temps de décroissance initiale, aboutissent à une qualité verbale médiocre. La qualité est faible pour des valeurs négatives du rapport signal-bruit, mais augmente rapidement pour des valeurs plus élevées. Dans les 'petite' et 'moyenne' salles, on obtient une qualité de communication verbale optimale avec un tapis et un traitement absorbant des parois/plafond, et avec des sièges non-absorbants. Dans la 'grande' salle, il faut un tapis, un traitement absorbant et des sièges absorbants. Le facteur le plus important régissant la qualité de communication verbale dans les salles est le bruit de fond.

1. INTRODUCTION

Non-optimal classroom acoustical design directly affects verbal communication by students and instructors, and reduces student learning proficiency. This is particularly true for students who are young, have a hearing loss or are working in a second language. Furthermore, it may cause voice problems for the instructor. Acoustical quality for verbal communication ('verbal-communication quality') is quantified here by the Speech Intelligibility (SI), the percentage of speech material which would be expected to be correctly identified by an average, normal-hearing listener working in their first language. A number of physical correlates of SI exist - Speech Transmission Index (STI) was used here. Ignoring factors related to instructor accent or enunciation, the STI and SI at a listener position in a classroom depend on two main factors – the speech-signal to background-noise level difference in decibels, and the classroom reverberation.

The speech level depends on the instructor voice level and on the classroom acoustical design – in particular, how the speech level decreases with distance from the instructor to the listener. The background-noise level comprises noise from the ventilation system, in-class equipment (such as projectors), in-class student-activity noise, and noise originating outside the classroom. In this study, noise from in-class equipment, and from outside the classroom was assumed negligible. Reverberation depends mainly on classroom size and on the amount of sound absorption - including that contributed by the classroom occupants. It is generally considered that, for excellent speech conditions, reverberation in the furnished, occupied classroom should be in the range 0.4 to 0.6 s, increasing with classroom volume, and that the speech-to-noise level difference should exceed a value of at least 15 dB. Given typical instructor speech levels, it is considered that classroom background-noise levels should not exceed about 35 dBA [1, 2].

The objective of the present research was to study, using previously developed empirical prediction models [3, 4, 5], the relationship between verbal-communication quality and classroom design, and thus to identify the optimal designs. This was done by predicting the variations of measures related to classroom verbal-communication quality with relevant classroom design parameters. Speech intelligibility is the main measure of interest in this study, because it quantifies verbal-communication quality.

Three sizes of classroom - referred to as 'small', 'medium' and 'large' - with capacities of 25, 100 and 400 students, were selected, with characteristics typical of university lecture rooms [5]. The 'small' classroom was 7.4 m by 7.6 m by 3.0 m high, the 'medium' classroom 10.7 m by 10.4 m by 3.5 m high, and the 'large' classroom was 24.1 m by 21.5 m by 5.7 m high. In each classroom, the source was at some distance from the front wall, denoted as the front-wall distance (*fwdist*) [5]. Nine symmetrically located receiver positions, with coordinates determined from the classroom dimensions, were selected, as defined in Figure 1. Room-average results were then calculated.

All of the classrooms were studied under the conditions of half occupancy and full occupancy. For each occupancy condition, the following design parameters were systematically changed, one at a time: A-weighted unoccupied background-noise level (BNA_u); carpet factor (*carpet*); wall/ceiling-absorption factor (*absorb*); and upholstered-seat factor (*upseat*). The *carpet*, *absorb* and *upseat* factors took values of either 0 or 1, corresponding to no or complete floor carpeting, wall/ceiling absorption and upholstered-seating, respectively. The three levels of background noise used were 30 dBA ('low' noise level), 40 dBA ('medium' noise level) and 50 dBA ('high' noise level).

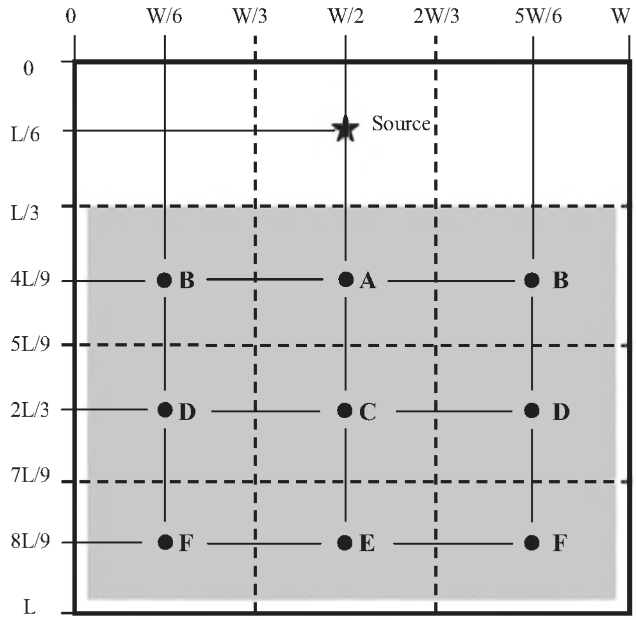

Figure 1. Diagram of a generic classroom, showing the generic source and received positions, with coordinates.

From the input data, a number of acoustical parameters that indicate verbal-communication quality were calculated. The main acoustical parameters of interest were the average unoccupied 1-kHz surface-absorption coefficient ($\alpha 1$), the 1-kHz occupied early-decay time ($EDT1_o$), the A-weighted occupied speech-to-noise level difference (SNA_o) and the A-weighted occupied background-noise levels (BNA_o). Based on these and other acoustical parameters, and the source-receiver distances, the classroom-averaged occupied speech intelligibility (SI_o) was calculated. From this, a qualitative verbal-communication-quality descriptor was assigned, as follows: $SI \geq 98$ % = 'Excellent' (E); $SI_o \geq 96$ % = 'Very Good' (VG); $SI_o \geq 93$ % = 'Good' (G); $SI_o \geq 88$ % = 'Fair' (F); $SI_o \geq 80$ % = 'Poor' (P); $SI_o < 80$ % = 'Bad' (B). Note that the assignment of these descriptors is conjectural and has not been validated experimentally.

2. STI / SI PREDICTION

Speech intelligibility *SI* was calculated from *STI* using a regression equation fitted to pairs of corresponding *STI* and 'short-sentence' *SI* values from Barnett and Knight [6]:

$$SI = -270.9\, STI^4 + 817.4\, STI^3 - 923.3\, STI^2 + 476.8\, STI - 0.009. \quad (1)$$

STI was calculated from the A-weighted speech-to-noise level difference (*SNA*) and the 1-kHz early-decay time (*EDT1*) using the procedure described by Steeneken and Houtgast [7]. At any position *r*, *SNA* can be determined from values of the A-weighted speech level ($SLA(r)$) and the background-noise level ($BGNA$):

$$SNA = SLA(r) - BGNA. \qquad (2)$$

As discussed in detail in [5], an important question is how to estimate realistic speech levels. Various options were considered and the following optimal one chosen. It predicts speech levels which both vary in a realistic way with source/receiver distance in individual classrooms, and which are derived from vocal output powers which vary with the prevailing acoustical conditions. Two empirical models were combined, as follows:

- first, instructor output-power levels LWA_{emp} were predicted using [4]:

$$LWA_{emp} = 54.8 + 0.5\, SANA + 0.016\, V - 9.6 \log (A_o), \quad (3)$$

  in which V is the classroom volume in m^3, A_o is the total classroom absorption in m^2, and $SANA$ is the total A-weighted student-activity-noise level in dBA, calculated from [4];

$$SANA = 83.0 + 10.0 \log (n) - 34.4\, A_o + 0.081\, A_o, \quad (4)$$

  where n is the number of seats;

- second, SLA_u intercepts, I_u in dBA, and slopes, s_u in dBA/dd (dd=distance doubling) were predicted using [3]:

$$I_u = 65.79 - 0.0105\, L + 1.5198\, fwdist - 1.4061\, absorb - 4.3186\, upseat; \quad (5a)$$

$$s_u = -1.208 - 0.0877\, L + 1.1401\, basic, \quad (5b)$$

  in which L and W are the classroom length and width, respectively, in m, and *fwdist* is the distance of the speech source from the nearest classroom surface (usually the front wall), in m. *absorb* indicates the amount of ceiling and/or wall absorption, and is equal to 1 with a full-coverage ceiling absorption. *upseat* is zero if the seats are non-absorptive, and 1 if they are padded and, therefore, sound-absorptive. *basic* is 1 if the classroom contains no sound-absorbing features, and 0 otherwise. These models were developed assuming vocal output levels corresponding to an average person speaking at between a normal and a raised voice. The output-power level LWA_{nr} corresponding to these levels can be easily estimated. Of course, if the output-power level changes, the intercept (SLA at 1 m), but not the slope, changes by the same amount;

- thus, for a given classroom, predicted intercepts were adjusted by an amount equal to the difference between the power levels predicted by Eq. (3) and that corresponding to levels used to predict the intercept by Eq. (5a):

$$I_u' = I_u - (LWA_{nr} - LWA_{emp}); \qquad (6)$$

- speech levels, $SLA_u(r)$ in dBA, at any source/receiver distance, r in m, were calculated from the resulting adjusted intercept I_u and the slope s_u predicted by Eq. (5b), as follows:

$$SLA_u(r) = I_u + s_u \log(r). \qquad (7)$$

Unoccupied SLA_u's were then corrected to the occupied condition (SLA_o) on the assumption of 70% classroom occupancy, typical of UBC classrooms, using diffuse-field theory:

$$SLA_o(r) = SLA_u(r) + 10 \log \frac{\left(\frac{1}{4\pi r^2} + \frac{4}{A_u}\right)}{\left(\frac{1}{4\pi r^2} + \frac{4}{A_o}\right)}, \qquad (8)$$

in which $A_o = A_u + 0.7nA_p$ is the occupied-classroom absorption, in m^2, and A_p=0.81 m^2 [8].

As for $EDT1_u$, values were predicted using diffuse-field reverberation theory and the total 1-kHz surface absorption coefficient $\alpha 1_{tot}$, as follows [4]:

$$EDT_u = 0.16\, V / (\alpha 1_{tot}\, S + 4mV), \qquad (9a)$$

with $$\alpha 1_{tot} = \alpha 1_{basic} + \alpha 1_{carpet} carpet + \alpha 1_{absorb} absorb + \alpha 1_{upseat} upseat. \qquad (9b)$$

The resulting values were corrected to the occupied condition ($EDT1_o$) on the assumption of 70% occupancy:

$$EDT1_o = \frac{0.16V}{\left(\frac{0.16V}{EDT1_u}\right) + 0.7nA_p}. \qquad (10)$$

This empirical model can be criticized for using the EDT to describe reverberation, instead of measures such as TI and $C50$ that more accurately account for details of the reverberation, and in not using frequency-varying values. However, it has been shown to give very similar predictions to those by more accurate models [9].

3. VARIATION OF VERBAL-COMMUNICATION QUALITY WITH DESIGN PARAMETERS

Let us consider how verbal-communication quality varies with the design parameters. As an example, Table 1 shows the variation of room-average speech intelligibility (SI) and quality with the four classroom design parameters, for the 'medium' classroom with half occupancy – the data is presented in order of decreasing quality.

Table 1. Predicted room-average SI and verbal-communication qualities for various design parameters in the 'medium' classroom with half occupancy, presented in order of decreasing quality.

'MEDIUM' CLASSROOM, HALF OCCUPANCY				
BNA (dBA)	*carpet*	*absorb*	*upseat*	*SI* (%) / Quality
30	1	1	0	97.0 / VG
30	0	1	0	96.7 / VG
30	1	1	1	96.4 / VG
30	0	1	1	96.3 / VG
30	1	0	1	96.3 / VG
30	1	0	0	96.2 / VG
30	0	0	1	96.1 / VG
30	0	0	0	95.7 / G
40	0	0	0	95.1 / G
40	1	0	0	94.9 / G
40	0	1	0	94.5 / G
40	1	1	0	94.5 / G
40	0	0	1	93.2 / G
40	1	0	1	92.9 / F
50	0	0	0	91.9 / F
40	0	1	1	90.9 / F
40	1	1	1	90.4 / F
50	1	0	0	87.4 / P
50	0	1	0	81.1 / P
50	1	1	0	78.9 / B
50	0	0	1	71.9 / B
50	1	0	1	67.4 / B
50	0	1	1	50.5 / B
50	1	1	1	46.3 / B

Results were similar at all positions in a given classroom, and for both occupancies. Verbal-communication quality generally decreased with increasing background noise. It generally decreased with increased occupancy, but the effect was small. Quality varied in a complex way with the absorptive features present. The optimal and worst-case verbal-communication qualities are highlighted in Table 1. The worst cases are predicted for a background noise of 50 dBA, and values of 1 for *carpet*, *absorb* and *upseat* (*i.e.* full-coverage carpeted floor, wall or ceiling absorption and upholstered seats – the maximum absorption). The optimal cases occur at a background noise of 30 dBA, with *carpet* and *absorb* equal to 1, but with *upseat* = 0 (*i.e.* non-upholstered seats). Strictly speaking, the worst case for both the 'small' and 'medium' rooms occurred at half occupancy. However, the verbal-communication qualities of both rooms in the optimal and worst cases fall into the ranges of 'Very Good' and 'Bad', respectively, for both occupancies.

The results were somewhat different for the 'large' classroom. The worst verbal-communication quality occurred with a background noise of 50 dBA, as in the other rooms, but with *carpet* = 0 (*i.e.* a non-carpeted floor) and 1 for *absorb* and *upseat*. The optimal verbal-communication quality occurred with a background noise of 30 dBA, as in the other cases, but with values of 1 for the absorption factors. In other words, more absorption was needed to achieve optimal quality than was the case in the smaller rooms. Again, *SI* and quality decreased with increased occupancy for the 'large' classroom, but corresponded to 'Good' verbal-communication quality for the optimal case, and to 'Bad' quality for the worst case, regardless of occupancy. The 'large' classroom had far less of an overall variation of speech intelligibility than the other two rooms, the best-case quality being lower and the worst-case quality being higher than in the 'small' and 'medium' rooms. The reason for such a contrast between the 'large' and the 'small' and 'medium' rooms is likely the fact that the former has a much greater volume than the others (2932.1 m^3 compared to 165.8 m^3 for the 'small' classroom and 389.0 m^3 for the 'medium' classroom). There is more of a volume difference between the 'large' classroom and either of the other two rooms than there is between the 'small' and 'medium' rooms.

In general, the background noise is the predominant design factor affecting verbal-communication quality in all rooms. It is interesting to note that, in all cases, at the highest level of background noise, the best verbal-communication quality occurs when there is no carpet, surface absorption or upholstered seats. It is also interesting to note that a change from non-upholstered seats to upholstered seats can significantly decrease the speech intelligibility when carpet and wall/ceiling absorption are present in a classroom with 'high' background noise.

4. ROOM-ACOUSTICAL PARAMETERS AND OPTIMAL VERBAL-COMMUNICATION QUALITY

Let us discuss in more detail the optimal verbal-communication qualities found for each classroom/ occupancy combination, and for what acoustical parameters they are attained. Table 2 shows the optimal verbal-communication quality predicted for each classroom/ occupancy combination, along with the corresponding design parameters and the predicted values of $\alpha 1$, $EDT1_o$, SNA_o and BNA_o. As can be seen from Table 2, the optimal verbal-communication quality ('Very Good') occurs at a

Table 2. Optimal verbal-communication quality for each classroom/occupancy combination with predicted $\alpha 1$, $EDT1_o$, SNA_o and BNA_o, and corresponding design parameters.

Classroom size, occupancy	BNA_u (dBA)	*carpet*	*absorb*	*upseat*	$\alpha 1$	$EDT1_o$ (s)	BNA_o (dBA)	SNA_o (dBA)	*SI* (%) Quality
'small', 0.5	30	1	1	0	0.23	0.42	29.2	16.3	97.3 VG
'small', 1	30	1	1	0	0.23	0.36	28.6	16.5	97.2 VG
'medium', 0.5	30	1	1	0	0.23	0.45	28.5	15.3	97.0 VG
'medium', 1	30	1	1	0	0.23	0.35	27.4	15.6	96.9 VG
'large', 0.5	30	1	1	1	0.34	0.64	29.5	13.7	95.8 G
'large', 1	30	1	1	1	0.34	0.57	29.0	14.5	95.7 G

value of $\alpha 1 = 0.23$ in the case of the 'small' and 'medium' class-rooms, regardless of occupancy. However, the optimal verbal-communication quality in the 'large' classroom ('Good', though at the top of the range) occurs at the slightly higher value of $\alpha 1 = 0.34$ for both occupancies.

Regarding *EDT*, the optimal verbal-communication quality occurs at a value of 0.42 to 0.45 s for the half-occupied 'small' and 'medium' rooms. The value is reduced to 0.35 to 0.36 s for these cases when the rooms are fully occupied. However, the optimal verbal-communication quality in the 'large' classroom occurs at a much higher value of 0.64 s when half occupied and 0.57 s when fully occupied. Class-room occupancy makes little difference to the range of optimal verbal-communication qualities attainable in any of the rooms. These results are fully consistent with current recommendations that reverberation times should increase from 0.4 to 0.6 seconds with classroom volume.

Referring again to Table 2, it can be seen that the optimal verbal-communication quality occurs in each classroom at slightly higher values of BNA_o when half occupied than when fully occupied. However, the values of BNA_o for the optimal cases of all classroom/occupancy combinations are within approximately 2 dBA of each other (27.4 to 29.5 dBA). This implies that the classroom size and occupancy are not major factors in determining the required BNA_o.

Although there is a single value of BNA_o corresponding to the optimal speech intelligibility attainable in each case, there is a range of values for which the optimal verbal-communication quality can be attained. Table 3 shows the range of BNA_o for which the optimal verbal-communication quality can be attained in each case. The results are also consistent with the belief that background noise should be less than 35 dBA.

Regarding speech-to-noise level difference, the optimal verbal-communication quality occurs in each classroom at slightly lower values of SNA_o when half occupied than when fully occupied (15.3 and 15.6 dBA for the 'medium' classroom when half and fully occupied, respectively). The optimal values of SNA_o get progressively lower as the room size is increased. Note that the optimal values are consistent with the recommendation that signal-to-noise levels should be at least 15 dBA to ensure high quality.

Although there is a single value of SNA_o corresponding to the optimal speech intelligibility attainable in each case, there is a range of values for which the optimal verbal-communication quality is attained. Table 3 shows these ranges of SNA_o.

Table 3. Ranges of SNA_o and BNA_o for which optimal verbal-communication quality is attainable, for the six classroom cases studied.

Classroom size, occupancy	Best verbal-communicatio	Optimal BNA_o range (dBA)	Optimal SNA_o range (dBA)
'small', 0.5	Very Good	< 40	5-25
'small', 1	Very Good	< 30	5-25
'medium', 0.5	Very Good	< 30	10-20
'medium', 1	Very Good	< 30	10-20
'large', 0.5	Good	< 40	7.5-20
'large', 1	Good	< 40	7.5-20

5. RELATIONSHIPS BETWEEN VERBAL-COMMUNICATION QUALITY AND ROOM-ACOUSTICAL PARAMETERS

Let us now look at the variation of speech intelligibility with each of the four predicted room-acoustical parameters $\alpha 1$, $EDT1_o$, BNA_o and SNA_o in each of the three rooms to see if there are interesting correlations. This was done for all three classrooms at half and full occupancies.

5.1 Classroom Absorption

In the six classroom-size and occupancy cases, $\alpha 1$ varied from 0.05 to 0.35. Figure 2 shows the variation of classroom-average *SI* with $\alpha 1$ for the case of the 'medium' classroom at half occupancy. The ranges of the various verbal-communication-quality categories are also indicated. As can be seen in the figure, a wide range of values of $\alpha 1$ is associated with 'Very Good' verbal-communication quality – the best attainable in the 'medium' classroom. However, these same values of $\alpha 1$ are also associated with lower verbal-communication qualities. Most of the values of *SI* are between 90 and 100 %, but there is a slight divergence at higher values of $\alpha 1$, for which the value of *SI* can be much lower. This occurs at high values of $\alpha 1$, with 'high' background noise. Therefore, it is expected that the worst verbal-communication quality for any of the given classrooms occurs with the highest value of $\alpha 1$ combined with the highest value of the unoccupied background noise (*i.e.* $SI < 50$ % for $\alpha 1 > 0.3$ and $BNA_u = 50$ dBA for the case of the 'medium' classroom at half occupancy). The results are quite similar in the other rooms. That a range of verbal-communication qualities is observed for a given value of $\alpha 1$ shows that there is not a predictable relationship between the two. Given this, and the fact that all six cases of classroom type and occupancy showed results similar to those in Figure 2, it can be concluded that the average surface-absorption coefficient alone does not determine the verbal-communication quality of the rooms.

5.2 Early-Decay Time

Regarding early-decay time, in the six cases, the values of $EDT1_o$ increased with increasing classroom size and decreased with occupancy. Values varied from 0.36 to 0.85 s. Figure 3 shows the variation of *SI* with $EDT1_o$ for the case of the 'medium' classroom at half occupancy. As can be seen in the figure, a wide range of values of $EDT1_o$ is associated with the optimal 'Very Good' verbal-communication quality in the classrooms. However, these same values of $EDT1_o$ are also associated with lower verbal-communication qualities. Most of the values for *SI* are between 90 and 100 %, but there is a slight divergence at lower values of $EDT1_o$, where the value of *SI* can be much lower. This occurs at low values of $EDT1_o$ with 'high' background noise. This trend is opposite in nature to that seen in the case of classroom absorption, where the divergence is at high values of $\alpha 1$. This makes sense, since high values of absorption imply low early-decay times. Thus, it is expected that the worst verbal-communication quality for any of the given rooms occurs at the lowest value of $EDT1_o$ combined with the highest value of unoccupied background noise (*i.e.* $SI < 50$ % for $EDT1_o < 0.4$ s in the case of the 'medium' classroom at half occupancy). The results are quite similar for the other rooms. The fact that a range of verbal-communication qualities is observed for a given value of $EDT1_o$, shows that there is no predictive relationship between the two. Given this and the fact that all six cases of classroom type and occupancy produce similar results, it can be concluded that the occupied early-decay time alone does not determine the verbal-communication quality of the rooms. This result contradicts common thinking that reducing reverberation increases verbal-communication quality. In fact, if reverberation is very low, due to high classroom absorption, then so too are speech levels and speech-to-noise level differences, a more significant detrimental effect.

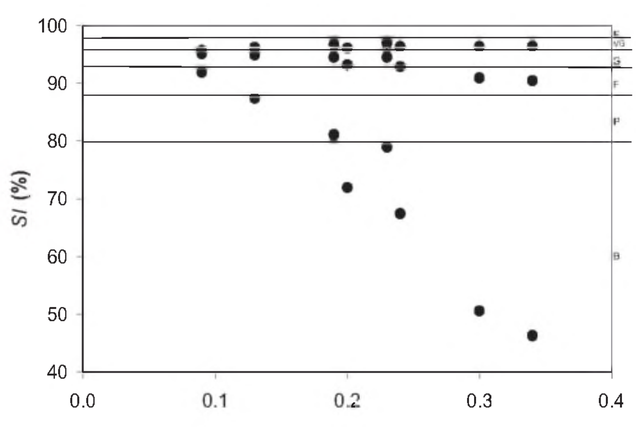

Figure 2. Variation of room-average SI with $\alpha 1$ for the 'medium' classroom with half occupancy.

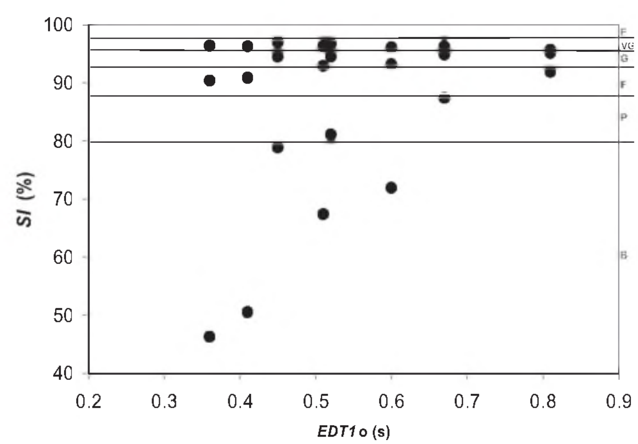

Figure 3. Variation of room-average SI with $EDT1_o$ for the 'medium' classroom with half occupancy.

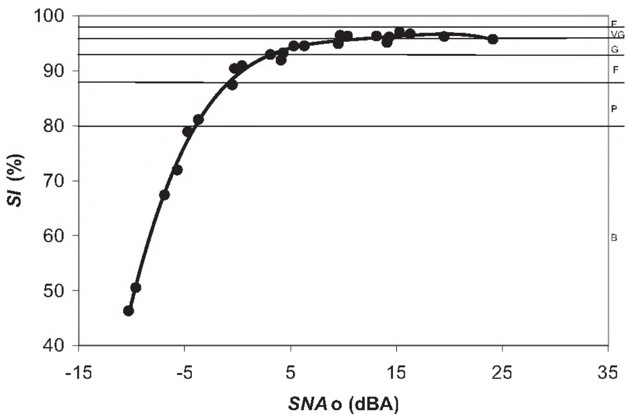

Figure 4. Variation of room-average SI with SNA_o for the 'medium' classroom with half occupancy.

5.3 Speech-to-Noise Level Difference

With respect to the signal-to-noise level difference, Figure 4shows the variation of *SI* with SNA_o for the case of the 'medium' classroom at half occupancy. The fourth-order trend polynomial fitted to the data is also shown. The plots for the other cases of *SI vs.* SNA_o are very similar. That is, there is a fairly constant level of *SI*, between 90 and 100%, at moderate to high levels of SNA_o, but a decrease of *SI* at lower levels of SNA_o. In particular, *SI* decreases rapidly for negative values of SNA_o. This decrease is very rapid for half and full occupancy in the 'small' and 'medium' classrooms, and less so for the 'large' classroom. From Figure 4, it can be seen that the speech intelligibility decreases with decreasing SNA_o. Thus, for a given classroom, the worst case of verbal-communication quality occurs at the lowest value of SNA_o (*i.e.* $SI < 50$ % for $SNA_o <$ -10 dBA for the case of the 'medium' classroom at half occupancy).

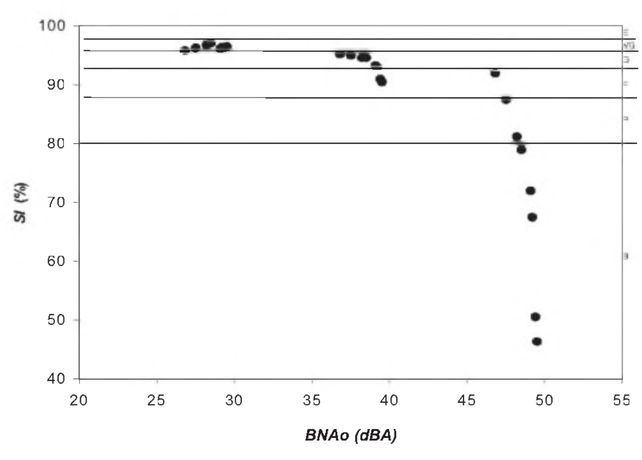

Figure 5. Variation of room-average SI with BNA_o for the 'medium' classroom with half occupancy.

5.4 Background-Noise Level

As for background-noise level, Figure 5 shows the variation of *SI* with BNA_o for the case of the 'medium' classroom at half occupancy. Plots of the other cases are similar. Of course, the data points are clumped around BNA_o values of 30, 40 and 50 dBA, the values tested here. With BNA_o near 30 and 40 dBA, most of the values of *SI* are at least 90%. However, with BNA_o near 50 dBA, there is a sharp decrease in *SI* in all six cases. This decrease is less steep with greater occupancy and/or increasing classroom size. Moreover, with increasing occupancy and/or increasing classroom size the 'clumps' of data mentioned above show more spread to lower levels of BNA_o. From Figure 5, it can be seen that the speech intelligibility decreases with increasing BNA_o. Thus, for a given classroom, the worst case of verbal-communication quality occurs at the lowest value of SNA_o (*i.e.* $SI < 50$ % for $BNA_o > 49$ dBA for the case of the 'medium' classroom at half occupancy).

6. CONCLUSION

From this study, the following conclusions can be drawn:

- Speech intelligibility (and verbal-communication quality) in the classrooms of the study did not depend solely on either classroom absorption or early-decay time in any systematic, predictable way. It is possible to get a wide range of values of *SI* for any given value of classroom absorption or early-decay time. However, it can be concluded that 'high' unoccupied background-noise levels, combined with either high absorption or low early-decay time, can lead to extremely low speech intelligibility;

- A common trend in the relationship between speech intelligibility and occupied background-noise level was observed. The speech intelligibility gradually decreased with increasing background noise until the highest levels of BNA_o, at which there was a very sharp decrease in verbal-communication quality. This decrease of *SI* gets less steep with increasing classroom size. 'Bad' verbal-communication qualities are possible in all of the cases, and these levels occur at slightly lower levels of BNA_o as the classroom size is increased. 'Very Good' and 'Good' verbal-communication qualities are attainable if BNA_o is sufficiently low, but this does not depend on occupancy;

- There was a close relationship between speech intelligibility and the speech-to-noise level difference. A fourth-order trend polynomial can be fit to the data with very high correlation. The speech intelligibility is low for negative values of the speech-to-noise level difference, but it increases sharply (more gradually for the 'large' classroom) to a fairly constant value. 'Bad' verbal-communication qualities are possible in all classroom/occupancy combinations studied for *SI* vs. SNA_o, where these verbal-communication qualities tend to appear at lower values of SNA_o as the classroom size is increased. Both 'Very Good' and 'Good' verbal-communication qualities are possible if SNA_o is sufficiently high, but size or occupancy does not make much of a difference;

- The most significant design factor in determining the verbal-communication quality of the rooms was the background noise. It was found that the verbal-communication quality generally decreases with increasing background noise. The 'large' classroom had less of a range of verbal-communication quality than the other two rooms.

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