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A survey of acoustic conditions in semi-open plan classrooms in the United Kingdom

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This paper reports the results of a large scale, detailed acoustic survey of 42 open plan classrooms of varying design in the UK each of which contained between 2 and 14 teaching areas or classbases. The objective survey procedure, which was designed specifically for use in open plan classrooms, is described. The acoustic measurements relating to speech intelligibility within a classbase, including ambient noise level, intrusive noise level, speech to noise ratio, speech transmission index, and reverberation time, are presented. The effects on speech intelligibility of critical physical design variables, such as the number of classbases within an open plan unit and the selection of acoustic finishes for control of reverberation, are examined. This analysis enables limitations of open plan classrooms to be discussed and acoustic design guidelines to be developed to ensure good listening conditions. The types of teaching activity to provide adequate acoustic conditions, plus the speech intelligibility requirements of younger children, are also discussed.
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I. INTRODUCTION

Open plan classroom designs became popular for educational reasons during the 1960s and 1970s. However, they were found to be impractical and difficult to teach in, and during the last two decades of the 20th century, there was a return to the more traditional enclosed classroom. Despite former problems, current educational and architectural trends are leading to a resurgence of open plan design with schools being built to accommodate shared teaching space in clusters of open plan classbases, large volume atria or breakout circulation space.[1–5]

When open plan schools were previously popular, research was carried out to investigate the levels of classroom and intrusive noise plus the effects of noise and ways in which it could be controlled. Although national and international acoustic design standards exist for schools and classrooms, relatively few contain specific criteria for open plan classrooms, and fewer still contain design guidance to achieve the criteria in practice and to optimize speech intelligibility.

With the current increasing popularity of open plan teaching areas, there is an urgent need to apply previous knowledge to the new designs. In the past, there have been no detailed surveys of the effects of noise intrusion and room acoustics on objective speech intelligibility in open plan schools. These effects are also influenced by the specific classroom layout and teaching activities.

Research has recently been undertaken to address this lack of data through acoustic surveys in 42 semi-open plan classrooms in UK primary schools (ages 5–11), plus subjective surveys of teachers' and children's attitudes to noise.[6] This paper presents the results of the acoustic surveys that have been used to examine the effects on noise and speech intelligibility of design factors such as acoustic finishes and number of classbases. The data have enabled relationships among Speech Transmission Index (STI), speech-to-noise ratio, and reverberation time in open plan classrooms to be established. The limitations of open plan designs have been examined and guidelines for use of such spaces for teaching and learning suggested.

II. BACKGROUND

A. Open plan classrooms

Progressive educational reform movements of the 1950s and 1960s replaced traditional didactic teaching (teacher speaking at the front of the class to pupils listening at desks) with a more informal child-centered approach.[7] A popular design accommodated several classes within one space with a shared resource area.[8] In a 1970s study, Bennet *et al*.[9] identified three main types of open plan classroom design: *fully open plan* (large degree of openness and teaching groups divided only by means of moveable furniture), *semi-open plan* (teaching spaces defined by means of walls but with large openings without doors in them), and *flexible open plan* (teaching group areas opened or closed off easily by means of sliding or folding partitions).

By the mid 1970s, 10% of all primary schools in England and Wales were open plan,[9] while in the U.S., over 50% of new build schools were either fully or semi-open plan.[10] However, during the 1970s and 1980s, there was criticism of this approach to learning and classroom design, and politicians and educators called for a return to more traditional values.[11] Many existing open plan designs were found

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to be impractical and difficult to teach in because of problems of noise and visual distraction,[9,12] leading to a return to enclosed classrooms. Many existing schools had remedial work to return to enclosed or semi-open plan layouts.[6] Apart from a brief revival of semi-open plan classrooms in the 1990s,[13] the majority of schools built in the UK in the latter part of the 20th century opted for enclosed designs.

In the 21st century, aspects of progressive education are again being encouraged in Europe and elsewhere[1–5] with new school designs incorporating large open spaces[14] to accommodate student centered educational philosophies and provide flexibility for a variety of teaching methods. However, there are already cases of some of these designs being enclosed and/or additional screening retrofitted to ameliorate problems with noise transmission.[2,15]

The classrooms surveyed in this study are of semi-open design, where it is intended that, within an open plan unit, each class is accommodated in their own main "classbase" area (where each class may be taught independently) while central areas such as the resource, practical areas, quiet room, and toilets are shared. Classes may occasionally come together for a shared plenary session in one classbase; however, in general, multiple, simultaneous activities occur in all classbases. The layouts of semi-open plan units generally fall into one of three types: linear, cluster, or annular, as shown in Fig. 1.

B. Previous studies of noise in open plan classrooms

A recent review[16] shows that there was a large body of research into various aspects of open plan classrooms in the 1970s. High noise levels and lack of acoustic privacy were frequently cited as major disadvantages, although opinions were divided on whether or not these would cause distraction or affect performance.[9,10,17–21] Often the *type* of noise (interfering speech or environmental sources, continuous or intermittent noise, and spectral characteristics) was considered to be more important than overall noise level in determining the degree of distraction.[10,19,22]

Noise surveys carried out in the 1970s showed that overall noise levels measured within occupied open plan classrooms were comparable to those measured in enclosed occupied classrooms;[16] the main difference was the intrusive noise level arising from adjacent spaces. Weinstein[23] suggested that the perceived increase in noise levels in open plan schools "may reflect a lack of control over the intrusive noise levels as much as the loudness level *per se*." Only two previous studies appear to have measured intrusive noise levels arising from neighboring spaces in the absence of main classbase noise;[21,23] these reported a range of 45-49 dB during "quiet" activities and up to 66 dB during "active" periods in adjacent spaces.

C. Speech intelligibility in classrooms

The STI takes account of both speech-to-noise ratio (SNR) and reverberation effects on speech communication and is widely accepted as the standard measure of objective speech intelligibility with an STI of between 0.6 and 0.75 corresponding to "good" speech intelligibility.[24] In standard enclosed classrooms, it is generally agreed that provided reverberation is reasonably well controlled, the SNR has the greater effect upon intelligibility.[25]

Normal-hearing young adults have been shown to understand familiar spoken material presented in SNRs of around 0 dB,[25–30] albeit with a greater listening difficulty rating than in higher SNRs.[31] However, children's speech perception does not approach that of adults until approximately 13–15 years of

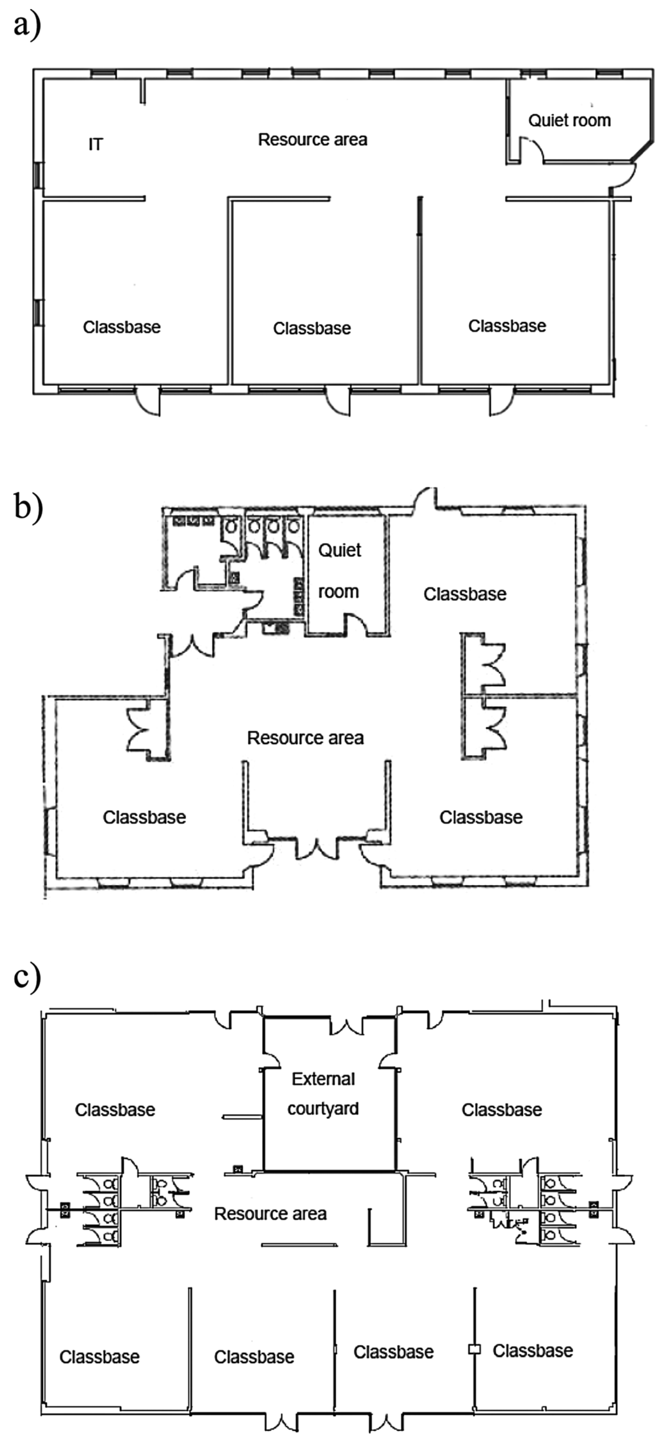

FIG. 1. Examples of semi-open plan design layouts. (a) linear design: classbases arranged in a line with their openings facing onto shared resource area; (b) cluster arrangement: classbases arranged around a central resource area with classbase openings facing onto each other; (c) annular design: classbases in a ring layout around a courtyard or other central enclosure.

age.[30] Several studies have shown that speech recognition in noise improves systematically with age. Bradley and Sato[27] carried out an experimental study of children's speech intelligibility in real classrooms with low reverberation times (around 0.45 s unoccupied). They concluded that between 8 and 15 dB SNR is required for young children, depending on age, to obtain intelligibility scores equivalent to those of young adults; the younger the listener the higher the requisite SNR.

D. Acoustic guidance for open plan classrooms

A review of international guidance on the acoustic design of schools[16] reveals that speech intelligibility criteria for standard enclosed classrooms are typically specified using combinations of maximum internal ambient noise level (30–35 dB L_{Aeq}) and reverberation time (0.4–0.9 s) according to the use of the space and type of student (in terms of age and hearing ability).

Although the current ANSI standard S12.60[28] discourages the use of open plan classrooms "*when good speech communication is desired*," other national standards on classroom acoustics contain criteria specifically for open plan classrooms, as shown in Table I. It can be seen that in addition to reverberation time and noise limits, the guidance both in Denmark[32] and in England and Wales[34] specifies criteria for speech intelligibility in open plan spaces in terms of STI. Within teaching groups, an STI of greater than 0.6 is required to provide "good" speech intelligibility, while in Denmark, an STI of less than 0.2 is also recommended between groups to provide good speech privacy.

The classrooms included in this survey were all built in England, before the introduction in 2003 of building regulations (Building Bulletin 93)[34] controlling the acoustical design of new schools in England and Wales.[34]

III. ACOUSTIC SURVEY PROCEDURE

Measurements were made of indoor ambient (unoccupied) noise levels, intrusive activity noise levels, STI and SNRs, and reverberation times.

Room acoustic parameters (STI and reverberation times) were determined from the impulse response measured using a maximum length sequence method (WinMLS 2004 PC based analyzer with professional soundcard) and omnidirectional [1/4 in.] microphone with built in pre-amplifier (Earthworks M30BX).

STI was measured using a head-sized loudspeaker (ASC MK III dual source high quality loudspeaker with main cone diameter of 100 mm and cabinet dimensions 145 × 115 × 210 mm) as the sound source, at a height of 1.6 m. The directionality of the sound source was measured and found to be sufficiently representative of that of a human speaker.[35]

Noise and simulated speech signal levels were measured at selected receiver positions at a height of 1.0 m above ground level using a hand held sound level meter (Larson Davis type 824).

A. Selection of schools and classrooms

Measurements were carried out in 42 open plan classbases in 12 primary schools (ages 5 to 11) across southern England. The schools were selected to represent the full range of open plan unit sizes (2 to 14 classbases), layouts (linear, cluster, annular), and date of construction (1973 to 1997). All classrooms were of semi-open or flexible open plan design.

The study focuses on single story semi-open plan designs that achieved 15-30 dB attenuation between the nearest adjacent classbase locations, measured in unoccupied conditions using a standard source.[6] The results may not necessarily be applicable to fully open plan classroom arrangements without screening, or to double height spaces, where sound attenuation between teaching groups would be significantly lower.

B. Classroom activities

Previous research has shown that noise levels in primary school classrooms depend on the classroom activity being undertaken as would be expected.[36] The current study focuses on the following activities involving speech:

(1) Whole class teaching: One person (student or teacher) speaking at any one time in the main classbase during instruction, discussion, etc. This is considered to be the most critical listening activity.
(2) Work at tables: Students working independently or in pairs or groups with some talking, while sitting at tables.
(3) Work with movement: Students working on activities that include movement around the classbase.

For the intrusive noise samples in all 12 schools, the most commonly occurring classroom activity was work at tables (58%), followed by whole class teaching (23%) and work with movement (19%). Observed activities were broadly consistent with findings from other studies;[37–39] therefore the samples were considered to be representative

TABLE I. National acoustic performance standards and guidance for open plan classrooms.

Country	Room type	RT (s)	Maximum ambient noise level L_{Aeq} (dB)	STI
Denmark (Ref. 32)	Open plan classrooms	<0.3-0.4[a]	30	within groups: > 0.6 between groups: < 0.2
Sweden (Ref. 33)	Open plan (landscaped) lecture space	0.4[b]	30	
England and Wales (Ref. 34)	Open plan classrooms	<0.8[c]	40	> 0.6

[a]RTs in each of 500, 1000, and 2000 Hz bands for unoccupied, furnished spaces.
[b]RTs in each of 500 and 1000 Hz bands for unoccupied spaces.
[c]Average of RTs in 500, 1000, and 2 000 Hz octave bands for unoccupied, unfurnished spaces.

of teaching activities occurring in primary school classrooms during a typical school day.

C. Measurement of indoor ambient noise level

The indoor ambient equivalent continuous noise level (L_{Aeq}) in unoccupied classrooms when the school is empty is the level due to sound sources such as external environmental noise or building services. The ambient noise level was measured over a 5-min period in the center of each classbase, after the school day had finished. As the noise level was judged subjectively to be fairly constant in each classbase, it was considered that this measurement would give a reasonable estimate of the indoor ambient level during the school day.

D. Measurement of intrusive activity noise

The intrusive L_{Aeq} noise levels were measured with the main classbase unoccupied and with normal activities being carried out in adjacent classbases. Multiple 2-min samples were measured at three positions in the main classbase; the dominant activity occurring in adjacent classbases being noted. In total, 561 samples were measured (an average of 4 or 5 samples per position or 13 or 14 measurements per classbase). To examine the variation in acoustic conditions around the classbase, three general measurement positions were chosen: at the "back" of the classbase near the opening (worst case), in the "middle" of the classbase; and at the "front" within 3 m of the teacher's usual speaking position (best case).

A 2-min measurement period was found in a previous survey[36] to give a good indication of fluctuations of noise within a classroom according to activity and does not interfere with teaching or children's concentration. In addition to overall A-weighted levels measured as $L_{\mathrm{Aeq,2min}}$, octave band sound pressure levels, $L_{\mathrm{eq,2min}}$, between 125 Hz and 8 kHz were recorded.

E. STI

The objective was to obtain STI for the most critical listening scenario, when the teacher is addressing a quiet and attentive class of students, in the main classbase. It is not easy to obtain true values of STI using the measured noise level from this activity as it is difficult to eliminate the teachers' voice from background noise. Furthermore, the STI will vary with different levels of intrusive activity noise. Therefore STI was measured in the main classbase, unoccupied, in accordance with BS EN 60268-16: 2003,[24] and adjusted as described in the following text to give realistic values for the occupied STI at different positions in the main classbase during varying activities in adjacent classbases.

It has been shown[40] that the modulation transfer function and hence STI may be determined from two independent measurements: the noiseless system impulse response (SNR >15 dB), and the measured active SNR at the receiver position. This method is convenient for when the true background noise levels excluding the speech signal (usually the teacher's voice) cannot be experienced in a practical measurement situation.

Measurements of the noiseless STI were carried out around the unoccupied classbase (adjacent spaces also unoccupied), with one source position and six receiver positions, arranged to represent the typical use of the classroom. Source and receiver heights were set at 1.6 and 1.0 m above floor level, respectively, as recommended in the UK standard.[34] The source was placed at the teacher's usual speaking position, facing into the center of the group of receivers.

The test signal (simulating the teacher's voice) was adjusted to 66.5 dB(A) at 1 m, the ANSI 3.5[41] level to represent the average spectrum for "raised" speech. The equalization was adjusted to ensure that the spectrum was correct to within ±1 dB. The noiseless room impulse response was then determined using the autocorrelation properties of the MLS signal.

From this, the STI value was calculated by correcting for the SNRs achieved for a variety of adjacent activities and scenarios. The intrusive activity noise arising from adjacent classrooms was accounted for using the noise level data obtained as described in Sec. III D.

In practice there would also be some noise arising from the presence of the children even while quiet and listening to their teacher.[27,36] To take account of the effect of this main classbase noise for a quiet, attentive class using a controlled method, a standard octave band spectrum for the specific occupied classroom noise level with "no student activity" based on measurements by Bradley and Sato[27] was used. This average noise level [equivalent to 44 dB(A)] is consistent with the average background noise levels of 42 to 46 dB(A) measured in primary school classrooms in the UK.[36]

It should be noted that classroom occupancy increases the sound absorption and hence decreases reverberation time, which would improve STI. However, for furnished classrooms with relatively low reverberation times, the change due to occupants is relatively small, around 10%.[27] Practical field studies have confirmed that the deleterious effect of occupancy noise on STI far outweighs any advantage to be gained from increased absorption due to occupancy.[42] Therefore the chosen STI calculation method was considered to be representative of a real occupied classroom situation, without needing to correct for absorption due to occupants.

F. SNR

As for STI, to represent occupied conditions both the A-weighted speech-to-noise ratio, S/N(A) and the weighted speech-to-noise ratio, S/N_w, were calculated from the measured simulated speech signal and intrusive noise levels, plus assumed main classbase occupancy noise level for each speech/noise combination.

S/N(A) is the difference between the overall A-weighted speech level ($L_{\mathrm{S,A,L}}$) and the overall A-weighted noise level (L_{AN}) at the receiver position. This has been shown to predict subjective intelligibility scores with similar accuracy to more complex parameters.[43]

S/N_w is calculated from the measured octave band L_{eq} values by summing together the weighted linear SNR in each octave band, the weightings being specified in BS EN 60268-16[24] (after Steeneken and Houtgast[40]).

G. Reverberation time

Both octave (125 Hz to 8 kHz) and third octave (100 Hz to 5 kHz) measurements of the T_{30} unoccupied, furnished reverberation time were obtained in accordance with ISO 3382,[44] using a sine sweep excitation signal to measure the impulse response. An omni-directional loudspeaker was used as the test source, located at a height of 1.6 m above floor level. Three receiver positions and two source positions were used for each classbase. At receiver positions the microphone was set at a height of 1.2 m above floor level.

Octave band measurements of T_{30} at 500, 1 000, and 2 000 Hz were arithmetically averaged to obtain the mid-frequency reverberation time, T_{mf} (the parameter used for the UK reverberation time performance standard[34]). Measurements of the mid-frequency early decay time, EDT_{mf}, were also obtained using a similar procedure, based on the first 10 dB of the decay curve.

IV. ACOUSTIC SURVEY RESULTS

A. Indoor ambient noise levels

Results were generally consistent between schools. The mean indoor ambient noise level across the 42 measured classbases was 35 dB $L_{Aeq,5min,}$ with levels ranging from 33 to 40 dB and a standard deviation of 1.6 dB.

In addition, 64% of the surveyed classbases had $L_{Aeq,5min}$ of less than 35 dB, satisfying the BB 93 standard for indoor ambient noise level in primary school classrooms. Those that exceeded this criterion (four schools) had subjectively significantly higher levels of building services noise or external road traffic noise (due to poor façade insulation).

Given that the ambient noise levels are low, it is reasonable to assume that the dominant source of intrusive noise is activity occurring within adjacent classbases and that ambient noise levels did not influence the STI measurements significantly.

B. Intrusive noise levels

A summary of the average measured intrusive activity noise levels is shown in Table II, which indicates a general trend for intrusive noise levels to increase with increasing activity in adjacent classbases. This is supported by the significant positive correlation found between adjacent activity ranking (1-3) and average intrusive noise level ($\rho = 0.57$, $n = 561$, $P < 0.001$).

TABLE II. Summary of intrusive noise levels from adjacent activities (main classbase unoccupied).

Adjacent activity	No. samples, n	Mean intrusive noise level, $L_{Aeq,2min}$ (dB)	Standard deviation (dB)
1. Whole class teaching	138	47	4.8
2. Work at tables	297	53	5.5
3. Work with movement	93	57	4.8

The mean octave band spectra for the different activities were examined and compared with the ANSI standardized spectrum for raised speech.[41] There was close agreement in spectral shape between 250 Hz and 4 kHz for all activities, suggesting that raised speech from adjacent classbases is the dominant noise source in this frequency range. This was confirmed by subjective observations during the survey.

The variation of intrusive noise across the measurement positions is shown in Fig. 2 for each activity (the number of samples is indicated on each bar). Figure 2 shows that in general, noise levels for each activity tend to increase as the position moves from the front of the class (nearer the teacher) to the "back" (nearer the opening and intrusive noise source). Partial correlation analysis shows that a significant positive correlation between intrusive noise level and activity type still occurs when the measurement position is controlled for ($\rho = 0.56$, $n = 525$, $P < 0.001$).

No significant relationship was found between measured intrusive noise level and design layout (linear, cluster, or annular).

C. SNR

The mean SNR results, S/N(A) and S/N_w, for both unoccupied main classbase (measured) and occupied main classbase (calculated) are shown in Table III. As expected, the SNR decreases with increasing level of activity in adjacent areas and as the measurement location approaches the "back" of the class, where speech levels are lowest and intrusive noise levels are highest.

The (predicted) occupied SNRs in the main classbase are up to 3 dB lower than for unoccupied results with the largest difference occurring for quieter adjacent activities and nearer the front of the classroom. The mean occupied SNRs achieved

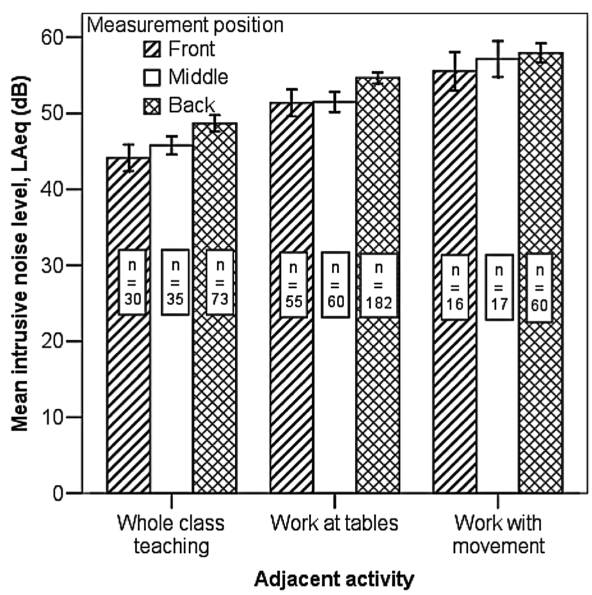

FIG. 2. Measured intrusive noise levels by activity and measurement position (error bars indicate 95% confidence interval)

TABLE III. Speech-to-noise ratios and STI by adjacent activity and measurement position (standard deviation shown in parentheses).

Adjacent activity	Measurement position	n	Main classbase condition: Unoccupied (measured) S/N(A) (dB)	S/N_w (dB)	STI	Quiet and occupied (calculated) S/N(A) (dB)	S/N_w (dB)	STI	Reduction in STI due to main classbase occupancy
Whole class teaching	Front	30	18 (4.4)	14 (3.6)	0.75 (0.07)	15 (3.0)	10 (2.3)	0.70 (0.06)	0.05
	Middle	35	14 (3.2)	11 (3.2)	0.71 (0.07)	12 (2.1)	9 (2.0)	0.67 (0.06)	0.04
	Back	68	9 (4.9)	6.8 (4.3)	0.61 (0.09)	8 (3.8)	5 (3.3)	0.58 (0.08)	0.03
Work at tables	Front	55	10 (6.6)	8 (5.7)	0.63 (0.16)	9 (5.9)	6 (4.8)	0.60 (0.14)	0.03
	Middle	60	9 (4.6)	6 (4.1)	0.61 (0.11)	8 (4.0)	5 (3.3)	0.57 (0.09)	0.04
	Back	160	4 (5.4)	2 (4.5)	0.50 (0.12)	3 (5.6)	1 (3.9)	0.48 (0.11)	0.02
Work withmovement	Front	10	8 (5.7)	6 (4.7)	0.59 (0.14)	7.7 (5.4)	5 (4.4)	0.55 (0.16)	0.04
	Middle	14	4 (4.4)	3 (3.6)	0.52 (0.10)	4 (4.2)	3 (3.2)	0.50 (0.09)	0.02
	Back	44	0 (7.6)	−1 (6.4)	0.44 (0.16)	0 (7.5)	−1 (6.2)	0.43 (0.11)	0.01

for these cases (12–15 dB) are likely to achieve a high value of STI and are therefore not critical. The difference was less pronounced (0–1 dB) for the other cases.

The mean S/N(A) results are 2-5 dB higher than the mean S/N_w results as the A-weighting network accounts for the fact that the human hearing system is less sensitive at lower frequencies. However the weighting factors used for S/N_w give the lower frequencies (125 and 250 Hz) similar weightings to those at mid-frequencies (500 and 1000 Hz).

D. STI

The mean measured values of STI are shown in Table III.

It can be seen that, as with the SNR, there is a trend for the STI to decrease with increasing level of activity and as the position moves toward the "back" of the class, further away from the speech source and nearer to the noise source. Significant negative correlation was found between STI and activity ranking ($\rho = -0.48$, $n = 509$, $P < 0.001$), and position ($\rho = -0.46$, $n = 476$, $P < 0.001$).

When the dominant activity in adjacent classbases was whole class teaching (that is, all classbases within the open plan unit engaged in coordinated critical listening activity), the average measured STI exceeded 0.6 ("good" speech intelligibility) for all positions, indicating that whole class teaching may be feasible in the main classbase under these circumstances. For work at tables in adjacent classbases, STI > 0.6 was achieved for the front and middle positions, while for work with movement, this criterion was achieved for the front position only. At the back of the class (near the opening), STI was less than 0.6 for both these activities. Therefore during critical listening tasks, if adjacent activities are not coordinated, children should be gathered close to the teacher away from the opening. Conditions of "excellent" speech intelligibility (STI > 0.75) are only achieved at the front of the classbase, in front of the teacher, when the adjacent activities are coordinated whole class teaching.

The mean STI results predicted for the main classbase when occupied are also shown in Table III. The estimated results suggest that good speech intelligibility (STI > 0.6) would only be achieved in the front and middle positions for adjacent whole class teaching activities. "Excellent" speech intelligibility is not achieved in this condition. The predicted reduction in STI due to occupancy of the main classbase, which varies from 0.01 to 0.05, is also shown.

It can be seen that, as for the S/N results discussed in Sec. IV C, there is generally a greater difference for positions at the front of the classbase. The just noticeable difference for STI, derived by Bradley *et al.*,[45] is 0.03. Therefore at the back of the classroom, it can be reasonably assumed that unoccupied main classbase measurements may be used to give sufficient indication of speech intelligibility during occupied, critical listening periods.

E. Reverberation time

Mean unoccupied mid-frequency reverberation times and early decay times measured in each school are presented in Table IV, averaged over all measurement positions and classbases. The presence of carpet or absorbent ceiling is also shown in the table.

T_{mf} results were reasonably consistent between measurement positions and classrooms for each school. However, EDT_{mf} generally showed a greater degree of variation between measurement positions. The mean EDT_{mf} was up to 0.1 s lower than the mean T_{mf}. A strong correlation was found between mean values of T_{mf} and EDT_{mf} ($\rho = 0.91$, $n = 114$, $P < 0.001$), as expected, see Fig. 3.

V. EFFECTS OF CLASSROOM DESIGN FACTORS

The relationships between measured noise levels and STI and factors relating to the physical design of the classroom were investigated to determine the optimal design of open plan classrooms to maximize speech intelligibility.

A. Effect of number of classbases

The effect of the size of an open plan unit on intrusive noise level was investigated by plotting mean L_{Aeq} intrusive noise levels (corrected to include main classbase occupancy) at the "back" of the classbase against the number of classbases within each unit as shown in Fig. 4, for both whole

TABLE IV. Summary of measured unoccupied reverberation times (standard deviation shown in parentheses).

School	Mean T_{mf}, s (% σ)	Mean EDT_{mf}, s (% σ)	No. classbases measured	Carpet?	Absorbent ceiling?	Approximate classbase volume (m^3)
9	0.26 (15.9)	0.24 (17.4)	3	Y	Y	104
1	0.31 (9.8)	0.26 (12.3)	1	N	Y	105
10	0.31 (14.3)	0.30 (12.3)	3	N	Y	104
11	0.33 (3.8)	0.25 (11.1)	2	N	Y	130
3	0.34 (8.7)	0.28 (12.7)	3	Y	Y	111
5	0.35 (6.3)	0.28 (13.0)	3	Y	Y	145
4	0.38 (9.4)	0.29 (8.2)	3	Y	Y	111
7	0.40 (4.6)	0.30 (10.1)	8	Y	Y	150
6	0.47 (8.2)	0.45 (11.6)	4	N	N	136
8	0.56 (3.3)	0.55 (4.7)	3	Y	N	204
2	0.61 (12.0)	0.61 (15.6)	3	Y	N	118
12	0.64 (6.2)	0.55 (20.6)	1	N	N	245

class teaching and pupils working at tables in adjacent classbases.

Figure 4 shows that the mean noise level tends to increase as the number of classbases increases, for both adjacent activities shown, as expected. In particular, it can be seen that there is a significant increase in mean noise level when the number of classbases increases above three. To determine whether this increase is significant, statistical t-tests were carried out to compare differences between unit sizes for various adjacent teaching activities.

A significant difference ($P < 0.001$) in mean intrusive noise level was obtained between units of up to three classbases and units of four or more classbases for each type of adjacent teaching activity (whole class teaching $t = 6.6$, df = 135; work at tables $t = 9.3$, df = 337; work with movement $t = 6.9$, df = 90) with significantly higher noise levels for units of four classbases or more. No significant difference ($P > 0.01$) in mean intrusive noise level was found between units of two and three classbases for any of the activities. Similarly, no significant difference was found between four and five or more classbase units for any of the adjacent activities. Therefore, in further analyses, results were grouped into those for "limited" units (2 or 3 classbases) and those for "large" units (4 or more classbases).

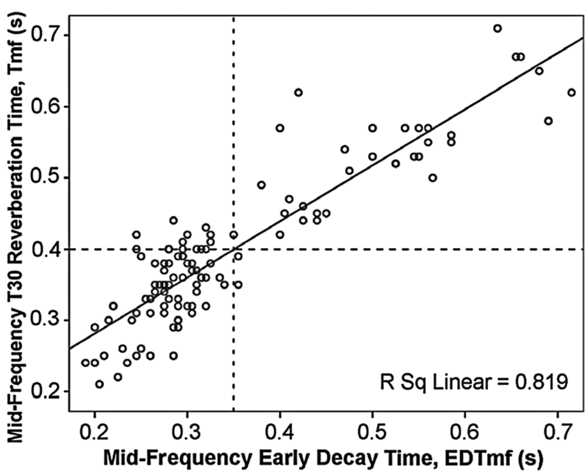

FIG. 3. Measured unoccupied mid-frequency reverberation times, T_{30} plotted against EDT.

The effect of unit size was further investigated by inspecting the STI within "limited" units ($n = 17$) and "large" units ($n = 25$) separately as shown in Figs. 5 and 6, respectively. Occupied mean STI results are significantly higher for limited units than for large units for whole class teaching ($F_{1,135} = 26.5$, $P < 0.001$) and work at tables ($F_{1,299}$ 60.1, $P < 0.001$) in adjacent classbases. No significant difference was found for work with movement.

B. Effect of sound absorbent ceiling

Provision of acoustic absorption is important to control noise levels and hence increase speech intelligibility. To investigate this factor in the context of open plan classrooms, the STI measured in classrooms with acoustically absorbent ceilings such as suspended mineral fiber tile, perforated metal, or wood fiber board (26 semi-open classbases) were compared to those with acoustically reflective ceilings such as painted plaster (11 classbases).

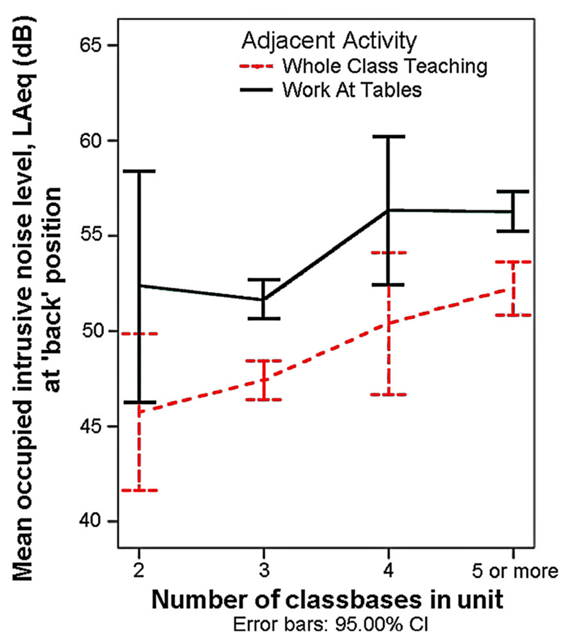

FIG. 4. (Color online) Intrusive noise level plotted against number of classbases in open plan unit.

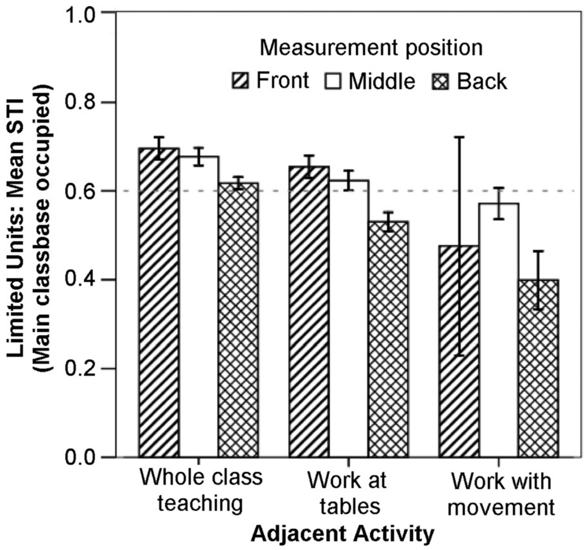

FIG. 5. STI as a function of measurement position and teaching activity in limited units (3 classbases or fewer).

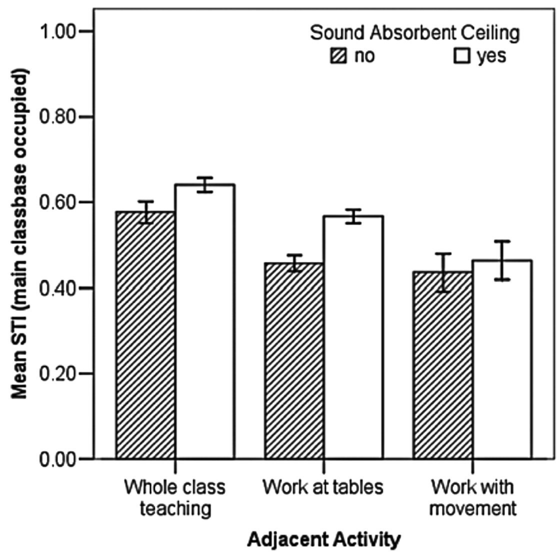

FIG. 7. STI as a function of adjacent activity for sound absorbent and sound reflective ceilings.

Figure 7 shows mean occupied STI plotted as a function of adjacent activity for classbases with and without acoustically absorbent ceilings. The average STI for each activity was higher for classbases with sound absorbent ceilings, as expected, with average increases of 0.07 STI for whole class teaching (that is, one person speaking); and 0.12 STI for work at tables (that is, several people speaking at once, distributed around the classroom). The higher increase for the latter adjacent activity is expected as the sound absorbent ceiling would provide greater reduction of reverberant noise in this case. Conversely, although the effect of the sound absorbent ceiling would be expected to be greater still for work with movement, the mean increase of 0.02 STI for this activity was not considered to be significant as it is within the just noticeable difference for STI determined by Bradley *et al.*[45] However, it should be noted that the sample size was considerably smaller than for the other two activities.

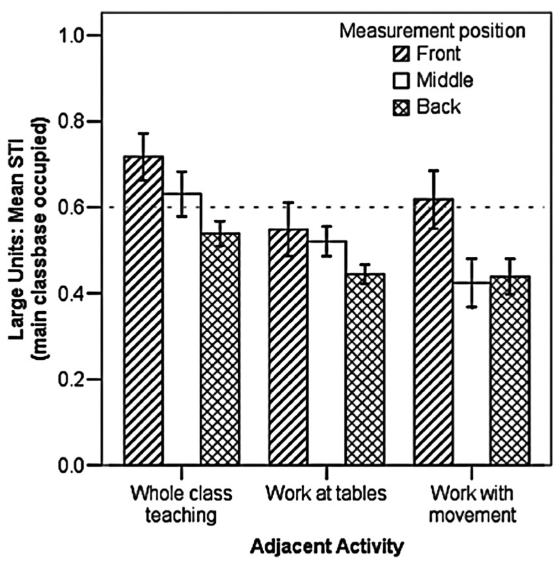

FIG. 6. STI as a function of measurement position and teaching activity in large units (more than 3 classbases).

Figure 8 shows the effect of acoustic finishes (sound absorbent ceiling and/or carpet) on mid-frequency reverberation time. This shows that classrooms with absorbent ceilings (with or without carpet) achieve a reverberation time of T_{mf} 0.4 s or less (as recommended by Danish[32] and Swedish[33] guidance for open plan classrooms), whereas classrooms without absorbent ceilings exceed this criterion. Carpet does not appear to be essential to control reverberation time, but is nonetheless beneficial to control footfall noise and noise from furniture movement.

The effect of sound absorbent ceilings on STI was further analyzed by considering the relationships between reverberation time and the noiseless, unoccupied STI. Because the entire open plan unit was unoccupied during the measurements of STI, the SNR was generally in excess of 15 dB, and therefore the STI was only affected by room acoustic conditions generally described by reverberation time. A significant negative correlation was found with STI being slightly more strongly correlated to EDT_{mf} ($\rho = -0.75$, $n = 114$, $P < 0.001$) than T_{mf} ($\rho = -0.72$, $n = 114$, $P < 0.001$), as expected.[43,46]

Figure 9 shows the relationship between EDT_{mf} and ambient STI for classbases with and without absorbent ceilings. The results fall into two distinct regions—those classbases

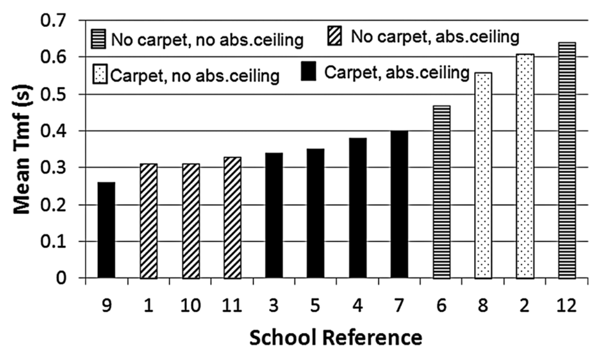

FIG. 8. Mean mid-frequency reverberation time measured in each school (over all classbases, all positions) as a function of basic acoustic finishes.

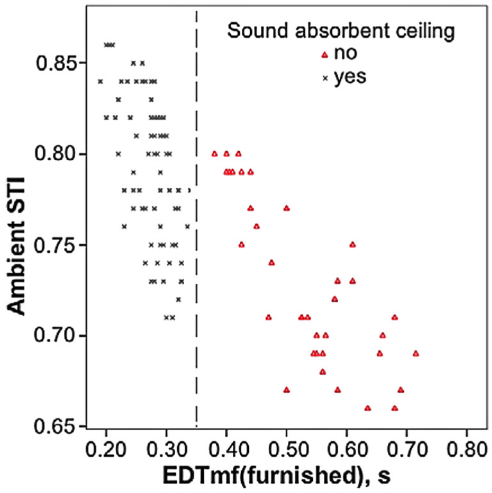

FIG. 9. (Color online) Ambient (noiseless) STI plotted against mid-frequency EDT for sound absorbent ceilings (x) and sound reflective ceilings (△).

with reflective ceilings with EDT_{mf} in excess of 0.35 s and those with absorbent ceilings with EDT_{mf} less than 0.35 s (to the nearest 0.01 s). For the latter case, the corresponding ambient STI achieved is at least 0.71 for all measurements. For classbases with reflective ceilings, the STI generally falls below 0.7 for higher early decay times ($EDT_{mf} > 0.6$ s).

For the occupied case, SNR and hence STI is degraded by the presence of intrusive noise. The unoccupied STI therefore needs to be as high as possible to ensure good speech intelligibility when the unit is occupied and intrusive noise is present. The cut off point between the two ceiling types of around EDT_{mf} 0.35 s would be a practical optimum design criterion to ensure sufficiently high STI levels. This corresponds to a T_{mf} value of around 0.40 s (see Fig. 3).

VI. RELATIONSHIPS AMONG STI, S/N, AND RT

This section considers the relationships among STI, SNRs, and reverberation times and uses multiple regression analysis to derive equations relating these parameters. The equations are then used to establish the required values of SNRs to achieve good and excellent speech intelligibility in an open plan classbase.

Figure 10 displays STI values plotted against S/N(A) for different ranges of reverberation time. Strong positive correlations were found between STI and S/N(A) ($\rho = 0.94$, $n = 508$, $P < 0.001$), and between STI and S/N_w ($\rho = 0.96$, $n = 508$, $P < 0.001$). A strong linear approximation exists between STI and S/N(A) up to around S/N(A) = 15 dB, after which a plateau is reached in line with STI theory.[24]

A similar relationship was found for S/N_w, which was slightly better correlated to STI than S/N(A) for obvious reasons, as STI theory uses the same weighting network as S/N_w. However, the relatively small difference between correlation coefficients would suggest that S/N(A) is an acceptable parameter to use for practical design purposes.

Results in Fig. 10 are split into data for shorter, "optimum" furnished reverberation times ($T_{mf} \leq 0.40$ s, or $EDT_{mf} \leq 0.35$ s) and longer reverberation times ($T_{mf} > 0.40$ s/$EDT_{mf} > 0.35$ s). For longer reverberation times, the STI

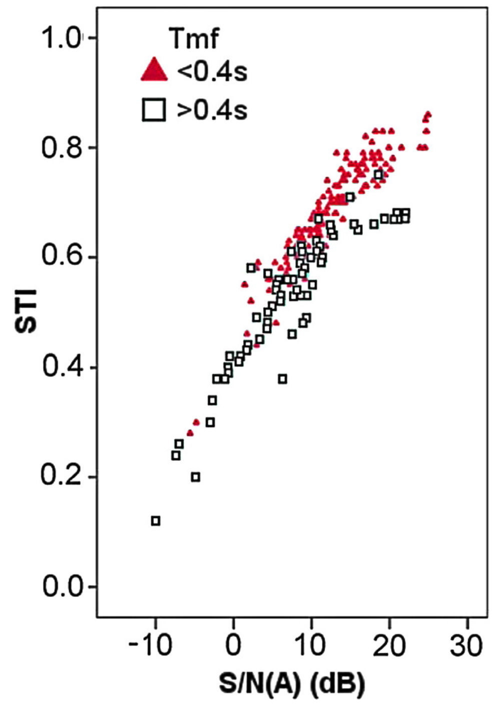

FIG. 10. (Color online) STI as a function of A-weighted speech-to-noise ratio, S/N(A), for optimum reverberation times of less than 0.4 s and longer reverberation times of greater than 0.4 s.

begins to plateau at lower SNRs because the STI becomes limited by the reverberation time at this point. However, for shorter reverberation times, the linear relationship continues to hold for higher SNRs.

Multiple regression anlysis was carried out over the linear portion of the data set to investigate the relationship among STI, SNR, and reverberation time (both EDT_{mf} and T_{mf}). S/N_w accounted for 91% of the variance in STI ($F_{1,167} = 1699$, $P < 0.001$). EDT_{mf} accounted for a further 3% of the variance ($F_{1,166} = 103$, $P < 0.001$). The regression equation relating STI, furnished EDT_{mf} and S/N_w is shown in Table V.

S/N(A) accounted for 88% of the variance in STI, ($F_{1,167} = 1\ 240.14$, $P < 0.001$) and furnished T_{mf} accounted for a further 2% of the variance ($F_{1,167} = 35.65$, $P < 0.001$). The regression equation for these predictors is also shown in Table V.

From Eq. (1) in Table V, it can be shown that, if reverberation time is controlled to a maximum EDT_{mf} of 0.35 s, then the minimum S/N_w to achieve STI $\geq$ 0.6 on average, is 6 dB.

Similarly, Eq. (2) in Table V shows that the equivalent minimum S/N(A) value to achieve STI > 0.6 (if reverberation time is controlled to $T_{mf} \leq 0.40$ s) is 8 dB.

VII. DISCUSSION

Current trends in school design have led to the frequent use of shared open space for teaching multiple groups of students simultaneously. It is important that the implications of these types of spaces on student's ability to hear and understand their teacher are fully understood. The data presented in this paper, plus analysis of the data in relation to various acoustic design parameters, enable the limitations and possibilities of teaching in open plan spaces to be assessed.

TABLE V. Multiple regression equations for predictors of STI.

Equation	Predictor	B	Standard error B	Beta	95% CI for B (lower bound)
1. $STI = 0.024(S/N_W) - 0.155(EDT_{mf}) + 0.513$	S/N_w	0.024	0.001	0.879	0.023
	EDT_{mf}	−0.155	0.015	−0.200	−0.186
2. $STI = 0.021[S/N(A)] - 0.131(T_{mf}) + 0.481$	S/N(A)	0.021	0.001	0.880	0.020
	T_{mf}	−0.131	0.022	−0.156	−0.175

The analysis shows that unless certain key acoustic, design, and classroom management criteria are fulfilled, open plan spaces are not ideal for teaching and learning owing to deficiencies in speech intelligibility. In particular, to maximize speech intelligibility in such spaces, mid-frequency reverberation times and early decay times should be low (less than 0.4 and 0.35 s, respectively); there should be no more than three classbases in an open plan unit; and teaching activities should be coordinated between all classbases in a unit (that is, all classbases involved in whole class teaching simultaneously, with one person speaking in each classbase). Where activities are not coordinated during critical listening periods, the furniture layout should allow students to gather within 3 m of the speaker. Even under these conditions, speech intelligibility may not be sufficient for all children.

Noise measurements in open plan classrooms confirmed that the major source of noise is intrusive speech in adjacent classbases. Intrusive noise levels decrease with increasing distance from the opening of the classbases and vary according to the type of activity being carried out. The intrusive noise affects the SNR in the classbase, which is lowest at the back of the class nearest the opening.

The average occupied S/N(A) results for coordinated whole class teaching for units of all sizes were compared with the findings of Bradley and Sato[27] that reported minimum SNRs required by the average student in different age groups. This suggests that provided reverberation times are reasonably well controlled and activities in open plan classrooms are coordinated 95% speech intelligibility could be achieved for children as follows:

- at all classroom positions for typical 11 yr olds [8.5 dB S/N(A) required on average].
- at the front and middle positions for typical 8 yr olds [12.5 dB S/N(A) required on average].
- at the front position only for typical 6 yr olds [15.5 dB S/N(A) required on average].

As with the SNR, the STI decreases with increasing activity noise levels in adjacent classbases and toward the back of the class. This highlights the importance of deriving a specific activity plan and seating layout at the design stage.

The relationship between STI and SNR was investigated. Considering the 95% confidence interval achieved for the linear part of the range, the results suggest that, provided reverberation times are well controlled (to $T_{mf} < 0.4$ s), to achieve a criterion of $STI > 0.6$ on average, a speech to noise ratio of at least 8 dB S/N(A) would be required.

Although SNRs in this range could be considered acceptable for adults and older children (over 11 yr), with normal hearing, a higher S/N(A) is recommended for younger children and more vulnerable listeners to achieve equivalent scores in speech intelligibility.[27] In view of this, it is likely that a standard of 0.6 STI may not provide the required S/N(A) for these groups, and thus, even if the optimal design criteria are achieved, the space may not be suitable for teaching younger children and those with communication difficulties. Based on regression Eq. (2) in Table VI, and assuming a reverberation time, T_{mf}, of less than 0.4 s, the estimated minimum STI values for younger listeners to achieve satisfactory speech intelligibility are as follows:

- 11 yr olds [minimum 8.5 dB S/N(A)]: STI 0.61.
- 8 yr olds [minimum 12.5 dB S/N(A)]: STI 0.69.
- 6 yr olds [minimum 15.5 dB S/N(A)]: STI 0.75.

Consideration of the physical design has shown that it is possible to achieve "good" speech intelligibility conditions ($STI \geq 0.6$) throughout the classbase when the size of the open plan unit is limited to three classbases and reverberation time is limited to 0.4 s T_{mf} (achieved by use of a highly efficient sound absorbent ceiling). Additionally, the unoccupied, noiseless STI should be at least 0.7. Working from these optimum design conditions, it is possible to provide guidance on suitable teaching activities to ensure good listening conditions throughout the main classbase.

Table VI shows mean results for occupied STI for those rooms surveyed that had optimal design conditions for semi-open plan classrooms (that is, reverberation time less than EDT_{mf} 0.35 s/T_{mf} 0.4 s; unit size 3 classbases or fewer).

The mean STI value minus one standard deviation has been considered to provide a more robust assessment of listening conditions. Table VI shows that for semi-open plan classbases with optimum design conditions, during critical listening periods in the main classbase, "good" speech intelligibility is likely to be achieved for all classroom positions

TABLE VI. STI in rooms with optimal design conditions.

Adjacent activity	Position	n	STI (main classbase quiet and occupied) Mean	σ
Whole class teaching	Front	18	0.72	0.03
	Middle	25	0.68	0.05
	Back	29	0.63	0.03
Work at tables	Front	22	0.67	0.06
	Middle	27	0.63	0.06
	Back	46	0.54	0.09
Work at tables with movement	Front	2	0.42	0.38
	Middle	4	0.60	0.02
	Back	4	0.39	0.04

when adjacent activities are coordinated. When adjacent classbases are working at tables, the main class should be gathered closely around the teacher on the floor (at the front position) to facilitate good listening conditions. When adjacent classbases are involved in work with movement, conditions in the main classbase would generally not be sufficient to achieve good speech intelligibility for critical listening activity. Therefore teachers should plan activities between classbases, so that work involving movement is coordinated and does not take place when other classbases are involved in critical listening activities such as whole class teaching.

VIII. CONCLUSIONS

A detailed survey of the acoustic conditions in a range of semi-open plan classrooms in primary schools has enabled the effects of noise on speech intelligibility in such spaces to be investigated. The objective results of the survey have been analyzed to examine relationships between speech intelligibility and various design factors of semi-open plan primary schools. This has shown that, unless certain guidelines are adhered to, it is not possible to design and use these spaces so that good speaking, listening and hence learning conditions can be achieved.

The key acoustic design criteria and classroom management strategies are as follows:

- Each semi-open plan unit should have no more than three classbases.
- The (furnished and unoccupied) mid-frequency reverberation time should not exceed 0.4 s.
- The (furnished and unoccupied) mid-frequency early decay time should not exceed 0.35 s.
- The (unoccupied) STI should be at least 0.7.
- Sound absorbent ceilings should be provided (and carpeted floor coverings are preferable).
- Activities involving movement should be coordinated between the classbases in a unit.
- For critical listening activities, when adjacent activities are not coordinated, children should be gathered around the teacher, away from the opening.

These results, based upon objective measurements, are of great relevance given the current trend in school designs, many of which incorporate extensive open plan areas. However, it has been shown that even when these criteria are satisfied, listening conditions may not be suitable for all age groups and listeners. In addition, certain human factors that are not revealed by the objective data need to be considered. These include individual teaching techniques, listener age and ability, and hearing acuity. Nevertheless, the criteria listed in the preceding text are supported by subjective questionnaire surveys of teachers and students[6,47] and hence form a good basis for consideration when it is intended to design and use open plan classrooms.

ACKNOWLEDGMENTS

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