# Control of noise for speech intelligibility in open plan classrooms

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## ABSTRACT

Speech intelligibility in open plan classrooms cannot be assured from standard classroom design criteria (indoor ambient noise levels, reverberation time, sound insulation) due to the extent of multiple teaching activities occurring within the space. As a consequence of independent teaching activities occurring simultaneously, open plan schools are often associated with high intrusive noise levels resulting in poor conditions for speaking and listening in the classroom.

With open plan classrooms becoming an increasingly popular design trend in the UK and elsewhere, it is critical that layouts are designed to control noise in order for new schools to be acoustically 'fit for purpose'. A detailed survey of speech intelligibility conditions in existing open plan schools (based on specific classroom layouts and activity plans) has not previously been undertaken. Our research work has addressed this lack of knowledge through objective and subjective acoustic surveys in 44 existing semi-open plan classrooms in primary schools.

This paper addresses the effect of critical physical design variables on speech intelligibility in semi-open plan classrooms, to achieve compliance with current UK standards (Building Bulletin 93)[1]. Subjective opinions of acoustic conditions (obtained through extensive student questionnaire surveys), have been considered in addition to the physical design of the classroom. From these combined assessments it is demonstrated that the number of classbases within the open plan unit and the selection of acoustic finishes for control of reverberation and sound transmission are major factors in the control of intrusive noise for speech intelligibility. However, coordination of specific teaching activities and classroom management strategies are equally important for control of intrusive noise.

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## 1. INTRODUCTION

The current building stock of open plan classrooms in UK primary schools consists largely of semi-open plan classbases with restricted openings to a shared area, to limit noise transfer. This is due to many fully open plan classroom designs from the 1960s and 1970s having since undergone remedial treatment to achieve either a semi-open plan or fully enclosed design, following widely recognized problems with control of intrusive noise levels from adjacent classbases. However, since 2003, Britain has witnessed a major new school building programme, with plans announced in 2006 to rebuild or refurbish 50% of all primary schools by 2021[2]. Open plan designs are becoming increasingly popular in many new build schools in both the primary and secondary sectors to achieve flexibility for personalised learning, a key part of the UK Government's current initiatives for education.

Since 2003, acoustic performance standards for open plan classrooms have been mandatory under Approved Document E of The Building Regulations[3] in England and Wales. The normal means of achieving compliance with the Regulations is to achieve the performance criteria set out in Building Bulletin 93: Acoustic design of schools (BB93)[1], which includes criteria for maximum reverberation times and maximum ambient noise levels for classrooms. In addition, for open plan teaching areas which are more complex, a minimum Speech Transmission Index (STI) criterion of 0.6 is proposed, which corresponds to 'good' subjective intelligibility for normal hearing adult listeners[4], see Table 1. Specific criteria relevant to open plan classrooms are also given in Danish[5] and Swedish[6] classroom design standards, as detailed in Table 1. No specific criteria are given for open plan classrooms in design standards and guidance for other countries.

**Table 1:** Design standards and guidance criteria for open plan primary schools

| Country | STI | Reverberation time | Ambient noise |
|---|---|---|---|
| England[1]: Open plan teaching areas | ≥ 0.6 | $T_{mf} \leq 0.8$* | $L_{Aeq\ (30min)} \leq 40$ dB |
| England[1]: Primary school classrooms and classbases | - | $T_{mf} \leq 0.6$* | $L_{Aeq\ (30min)} \leq 35$ dB |
| Denmark[5]: Open plan classrooms | > 0.6 (within teaching spaces) < 0.2 (between teaching spaces) | < 0.3-0.4$^{+}$ | $L_{Aeq} \leq 40$ dB |
| Sweden[6]: Open plan lecture space | - | 0.4$^{++}$ | $L_{Aeq} \leq 30$ dB |

* Arithmetic average of RTs in 500,1k and 2k Hz bands for unoccupied, unfurnished spaces
$^{+}$125 - 4k Hz unoccupied spaces. 30% increase tolerable at 125 Hz
$^{++}$250 - 4k Hz unoccupied, furnished spaces

## 2. METHOD

The objective survey assessment method in the current research focused on teacher-to-student communication as the most critical aspect of speech communication within the classroom. The full survey procedure is detailed elsewhere[7,8]. All room acoustic parameters were measured using the WinMLS 2004 PC based software analyser, which uses a maximum length sequence signal (MLS) for excitation, where the average spectrum and level for 'raised' speech[9] is represented within the test signal. The noiseless room impulse response is

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determined using the autocorrelation properties of the MLS signal. From this, the STI value can be calculated by correcting for the actual speech-to-noise ratio achieved in various conditions during post processing, based on measured intrusive noise levels during active periods. The octave band intrusive noise level ($L_{eq}$) was measured using a hand held sound level meter in three main positions in each classbase: at the back of the classbase near the opening (worst case), in the middle of the room; and at the front within 2-3 m of the teacher's usual speaking position (best case). The dominant activity occurring in adjacent classrooms during the measurement period was also recorded. A short, two minute, measurement period was used, to capture the variation of the fluctuating noise levels.

A head sized loudspeaker was used as the test source, located at the teacher's usual speaking position. Laboratory measurements were carried out and compared with those of a mouth simulator to validate the use of the loudspeaker as a test source[7].

For the subjective survey, a questionnaire was developed to investigate children's perceptions of noise and acoustic conditions operating in each of the classbases used in the objective survey. The main objectives of the questionnaire were a) to establish the principal sources of background noise experienced in open plan classrooms, and perceived annoyance of different noise sources (with questions presented as dichotomous yes-no answers) and b) to investigate subjective impressions of ability to hear the teacher under different listening situations (using a five point Likert Rating scale (1 - very well, 2 – well, 3 – ok, 4 – not very well, 5 - not at all). Details of the questionnaire design and development may be found in elsewhere[6,7]. At least one in three randomly selected children from each classbase participated in the survey (749 children in total, 747 valid responses returned).

## 2. RESULTS

It should be noted that this study focuses on single height semi-open plan classroom designs which achieved 15 - 30 dB attenuation between nearest adjacent teaching locations (see reference 7 for full investigation). The results of this study would not be applicable for fully open plan classroom arrangements without screening, because in these situations sound attenuation would be significantly lower.

### A. Effect of unit size

The effect of unit size on intrusive noise level was investigated by plotting overall $L_{Aeq}$ intrusive noise levels (main classbase quiet and occupied) measured at the 'back' of the classbase according to the number of classbases within each unit (Figure 1). Error bars indicate a range of ±2 standard errors.

From examination of these data, it can be seen that the mean noise level tends to increase as the number of classbases increases, for both whole class teaching and work at tables, as expected. To determine whether the observed increase in intrusive noise level with unit size was significant, statistical t-tests were carried out to compare difference between unit sizes for various different 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 different type of adjacent teaching activity (one person is talking, individual work at tables, and individual work with movement), with significantly higher noise levels for units of four classbases or more. No significant difference ($p \geq 0.05$) 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 for intrusive noise levels between four and five or more classbase units, for any of the adjacent activities. Therefore, in further analyses, results were analysed by grouping measurements into 'limited' units (2-3 classbases) and 'large' units (4 or more classbases).

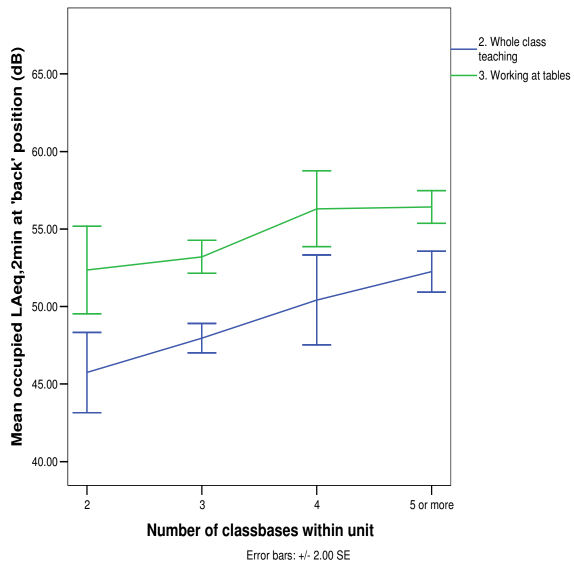


**Figure 1:** Mean intrusive noise level vs. number of classbases

Mean measured STI results are shown in Table 2. These data are based on the actual intrusive noise level recorded for each sample measurement position ('front', 'middle', and 'back') for different adjacent activities. A standard measured noise spectrum was used to represent the main classbase when the students are quiet and listening to their teacher in order to simulate occupied main classbase conditions[7]. The standard deviation is included to describe STI since the mean results alone are not sufficient to describe the degree of variation in STI over multiple measurements. There is a general trend for the STI to decrease with increasing level of activity, and as the position moves towards the 'back' of the class (further away from the speech source and nearer to the noise source).

**Table 2:** *Mean STI results calculated for main classbase occupied*

| Adjacent activity | Position | n | Mean occupied STI | σ |
|---|---|---|---|---|
| 2. One person talking | Front | 30 | 0.70 | 0.06 |
| | Middle | 35 | 0.67 | 0.06 |
| | Back | 68 | 0.58 | 0.08 |
| 3. Individual work at tables | Front | 53 | 0.59 | 0.14 |
| | Middle | 59 | 0.57 | 0.09 |
| | Back | 156 | 0.48 | 0.11 |
| 4. Individual work with movement | Front | 9 | 0.59 | 0.07 |
| | Middle | 13 | 0.49 | 0.09 |
| | Back | 39 | 0.44 | 0.10 |

Average STI results are considered as a preliminary indication of the likely activity plan necessary for BB93 compliance. For coordinated activities (adjacent classbases engaged in whole class teaching with one person talking at any time), the average measured STI exceeded the BB93 criterion of STI > 0.6 at front and middle positions, indicating that whole class teaching may be feasible under these circumstances (that is, with the class gathered more closely around the teacher, as is common in primary school settings). For other adjacent activities, average STI values indicate that BB93 compliance would not be achieved.

Results were further investigated by inspecting the mean STI for classbases within 'limited' units (n = 17) and 'large' units (n = 25) separately, as shown in Figure 2. Occupied mean STI results are significantly better for limited units than for large units ($F_{1,509} = 100$, $p < 0.001$). For the limited units, compliance is achieved for all positions when adjacent activities are co-ordinated, and for the front and middle positions during individual work at tables. For the larger units, compliance is only achieved for coordinated activities (one person talking in adjacent classbase), for the front and middle positions. Although compliance is indicated for individual work with movement for the front position here, the result should be treated with caution as the small number of samples (n = 1) is unlikely to be statistically reliable.

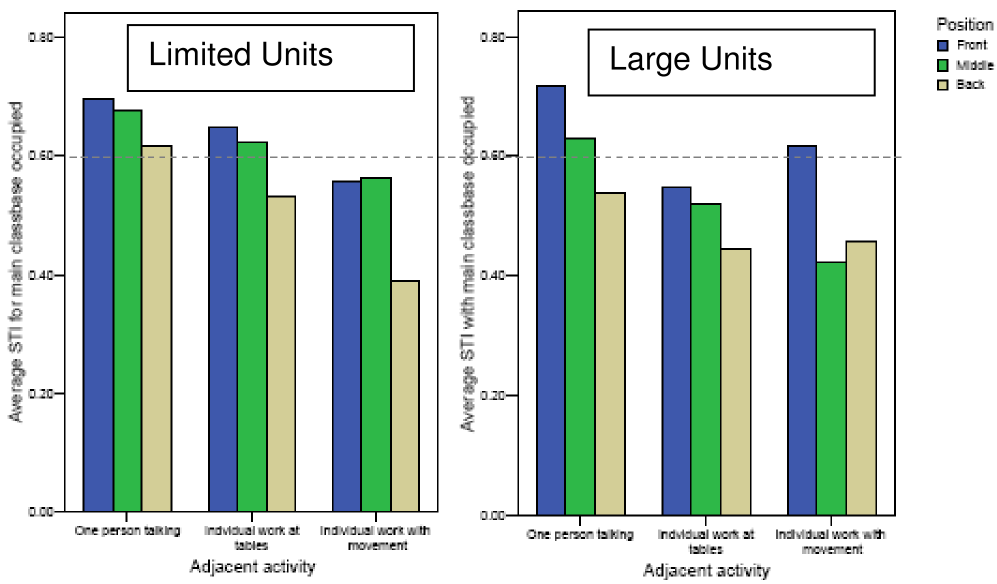


**Figure 2**: Mean occupied STI for limited and large units

Results of the subjective survey were found to support this finding from the objective survey. Children's reported hearing and annoyance from other teachers' voices and other pupils is shown below for 'large' and 'limited' units. There was a significant difference between unit size and reported frequency of hearing both teachers and pupils in adjacent classbases. Children in 'large' units were significantly more likely to report hearing other teachers voices ($\chi^2 = 5.41$; df = 1; p = 0.02) and pupils from other classbases ($\chi^2 = 5.54$; df = 1; p = 0.02), than children in 'limited' units. Children in larger units were also significantly more likely to report annoyance from other teachers voices ($\chi^2 = 9.36$; df = 1; p = 0.002) than children in limited units. However no significant difference was found between units of different sizes for annoyance from pupils in other classbases.

Mean listening ratings were generally worse for children in larger units than for those working in limited units (Table 3). A significant difference was found between limited and larger units for ability to hear the teacher when the adjacent classroom was working and moving around the classroom (U = 19159, p < 0.01) and for ability to hear another child answering the teacher (U = 19329, p < 0.01). No significant difference was found for other listening scenarios.

Dissatisfaction rates between large and limited units (% children hearing not very well, or not at all) were similar when adjacent classbases were quiet, but were significantly greater for larger units with intrusive noise present. Dissatisfaction rates rose to 'unacceptable' levels[7,10] for larger units when adjacent activities involved movement, but stayed at a acceptable level for limited units.

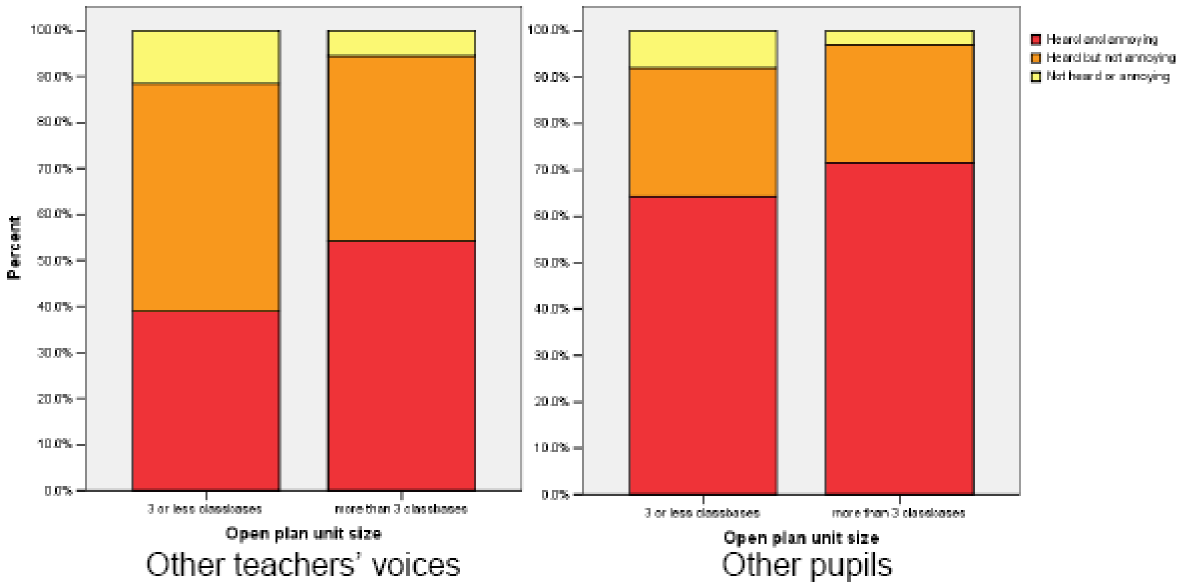


**Figure 3**: Children's reported hearing and annoyance of speech sources

**Table 3:** *Mean listening ratings – effect of open plan unit size*

| | Limited units (n = 168) | | | Large units (n=278) | | | Sig. |
|---|---|---|---|---|---|---|---|
| | Mean | σ | % hearing not very well or at all | Mean | σ | % hearing not very well or at all | p |
| <u>How well can you hear your teacher when adjacent classes are:</u> | | | | | | | |
| 1. Quiet (test) | 1.62 | 0.87 | 4 | 1.67 | 0.91 | 4 | NS |
| 2. Working at tables | 2.33 | 0.96 | 10 | 2.44 | 1.08 | 18 | NS |
| 3. Working at tables and moving around | 2.88 | 1.15 | 26 | 3.16 | 1.11 | 42 | 0.007 |
| <u>How well can you hear you classmate when:</u> | | | | | | | |
| 4. They are giving an answer | 2.02 | 1.06 | 13 | 2.27 | 1.03 | 13 | 0.007 |
| 5. You are working in groups | 2.25 | 1.17 | 14 | 2.31 | 1.23 | 20 | NS |

Mean STI measurements (averaged for each classroom, all positions) compare well with corresponding mean subjective listening ratings, as shown in Table 4. Since the subject's usual listening position in the classroom was not known, it was not possible to compare perceived listening ability with the variation of objective speech intelligibility around the classroom. The differences in mean listening ratings between large and limited units also support the objective findings that mean occupied speech intelligibility is significantly higher in limited units than large units.

**Table 4:** Comparison of mean STI and mean rated ability to hear teacher by unit size

| | Limited units | | Large units | |
|---|---|---|---|---|
| | Mean rating | Mean STI | Mean rating | Mean STI |
| 1. Quiet (test) | 1.6 Very well – Well | 0.65 Good | 1.7 Very well – Well | 0.57 Fair |
| 2. Working at tables | 2.3 Well – OK | 0.57 Fair | 2.4 Well – OK | 0.49 Fair |
| 3. Working at tables and moving around | 2.9 Well – OK | 0.53 Fair | 3.2 OK – Not very well | 0.43 Poor |

## B. Effect of sound absorbent finishes and reverberation time

Mid-frequency reverberation times ($T_{mf}$) as measured for unoccupied but furnished classrooms are presented for comparison with BB93[1] performance standards in Figure 4. Mean $T_{mf(furnished)}$ results for each school presented in Figure 4 have been averaged for each school over all measurement positions and classbases (results were consistent between measurement positions and classrooms for each school). Figure 4 also highlights the type of acoustic finishes (carpet, continuous sound absorbent ceiling or both) in each classroom. This shows that classrooms with absorbent ceilings (with or without carpet) achieve a mid-frequency reverberation time of less than 0.4 s (as recommended by Danish[5] and Swedish[6] guidance for open plan classrooms). Classrooms without absorbent ceilings exceed this criterion. Carpet does not appear to be essential to control reverberation time, as expected, but is beneficial to control footfall noise.

All classrooms met the BB93[1] maximum criterion for open plan teaching areas (maximum $T_{mf}$ 0.8 seconds) and all except two schools met the BB93 requirement for primary school classbases (maximum $T_{mf}$ 0.6 seconds). It should be noted that measurements were carried out in furnished classbases, and the reverberation time is likely to be slightly higher when measured without furniture or fittings in place (as required by BB93[1]). However, those rooms with absorbent ceilings (with or without carpet) are still likely to meet BB93 requirements for primary school classbases.

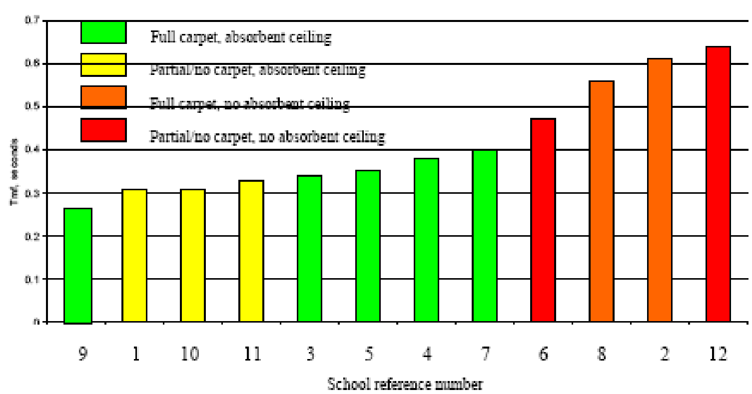


**Figure 4**: $T_{mf(Furnished)}$ averaged over all measurement positions for all classbases within each school

The effect of reverberation time on STI was examined by considering unoccupied (ambient) STI. Since the entire open plan unit was unoccupied during these measurements, the speech-to-noise ratio is generally in excess of 15 dB and therefore the STI is only affected by room acoustic effects best described by Early Decay Time (EDT). A significant negative correlation was found between STI and $EDT_{mf}$ ($r = -0.75$, $n = 114$, $p < 0.001$). A slightly lower but still significant correlation was also found between STI and $T_{mf}$ ($r = -0.72$, $n = 114$, $p < 0.001$).

Figure 5 shows the relationship between $EDT_{mf(furnished)}$ and ambient STI. The results fall into two distinct regions – those classbases with non-absorbent ceilings (highlighted in red) which have $EDT_{mf}$ in excess of 0.35 seconds, and those with acoustically absorbent ceilings (highlighted in green) with $EDT_{mf} < 0.35$ seconds For the latter case, the corresponding ambient STI achieved is at least 0.71 for all measurements. For classbases with acoustically reflective ceilings, STI falls below 0.7 for higher early decay times (> 0.6 s).

For the occupied case, speech-to-noise ratio and hence STI is degraded by the presence of intrusive noise. The ambient STI therefore needs to be as high as possible to ensure that the BB93 criterion is still achievable when the classbases are occupied (whilst being in line with the limitations of the design cost). The cut off point between the two design types (sound absorbent ceiling vs. no sound absorbent ceiling) is around $EDT_{mf(furnished)}$ 0.35 seconds which would be an optimum design criterion to ensure sufficient ambient STI. For practical design purposes, this corresponds to a $T_{mf(furnished)}$ of around 0.40 seconds[7].

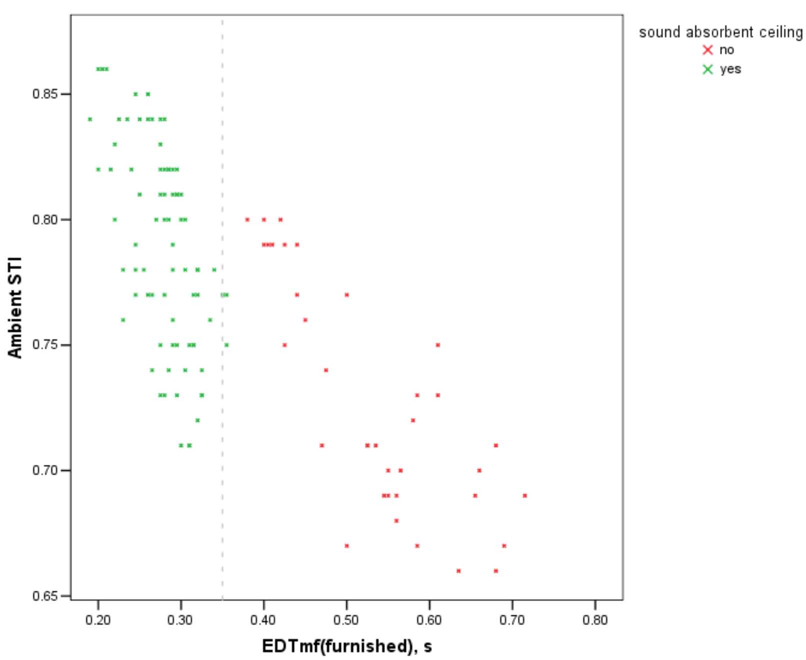


**Figure 5**: Ambient STI *vs.* $EDT_{mf(furnished)}$

The effect of reverberation time on STI with intrusive noise present is demonstrated in Figure 6. Results are split into data for shorter, 'optimum' reverberation times ($T_{mf,\ furnished} \leq 0.40$ seconds highlighted in green) and longer reverberation times ($T_{mf,\ furnished} > 0.40$ seconds highlighted in blue). A linear relationship is evident up to approximately S/N(A) 12 dB before the STI begins to plateau. For longer reverberation times, the STI begins to level off at lower speech-to-noise ratios, since the STI becomes limited by the reverberation time at this point. However, for shorter reverberation times, the linear relationship continues to hold for higher speech-to-noise ratios, resulting in a 'double tail' relationship.

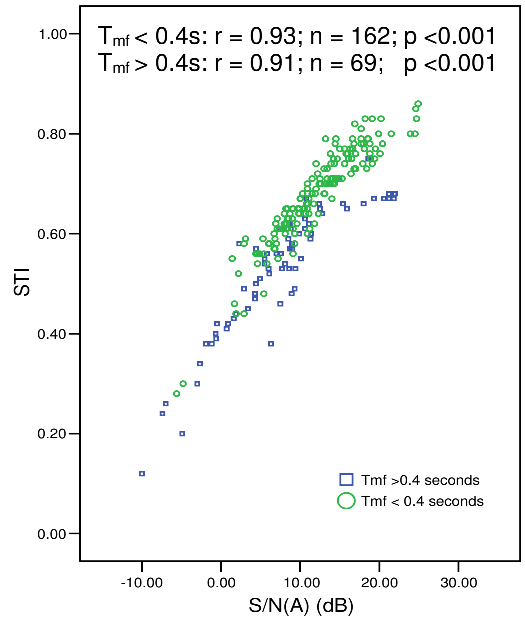


**Figure 6**: STI vs. S/N(A) – effect of reverberation time

Inclusion of a fully sound absorbent ceiling is found to be extremely beneficial since it not only shortens reverberation times to increase speech intelligibility, but also helps to control reverberant noise build up and noise transmission from adjacent spaces. Figure 7 shows mean percentile intrusive noise levels ($L_{A10}$, $L_{A90}$ etc) plotted as a function of adjacent classbase activity for classbases with and without acoustically absorbent ceilings (main classbase unoccupied). Average intrusive percentile noise levels for each activity are considerably lower for classbases with sound absorbent ceilings, as expected, with an average 2-3 dB reduction in noise level for activities 2 and 4, and a 6-7 dB reduction for activity 3. As a guide, a 6 dB reduction in noise level would correspond to an increase in STI of 0.13, all other factors being equal.

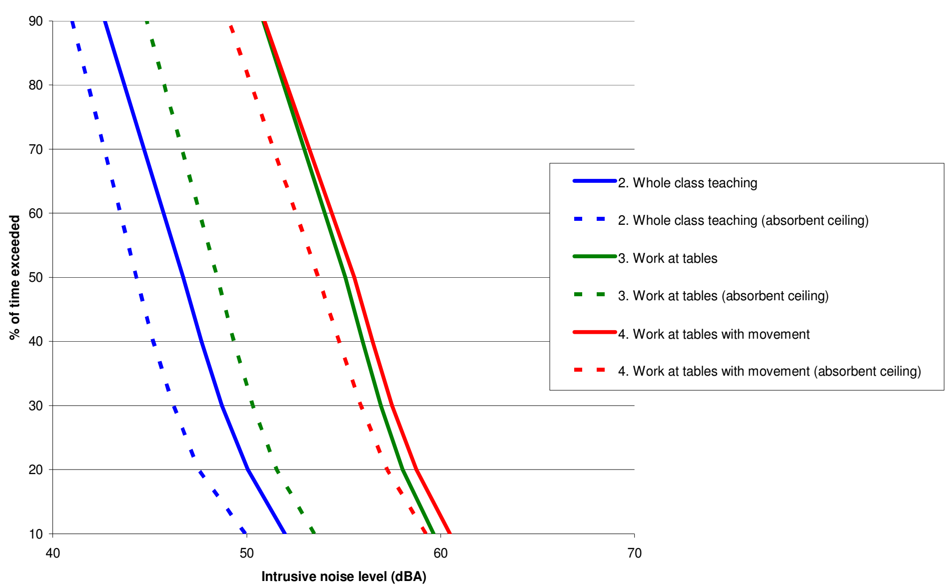


**Figure 7**: Intrusive percentile noise levels *vs.* ceiling type

## 3. CONCLUSIONS

This paper has concentrated on two emerging physical design parameters to demonstrate their effect on noise control and speech intelligibility within semi-open plan classrooms. The number of classbases sharing the open plan unit is a significant factor determining the intrusive noise level and hence objective speech intelligibility within each classbase for whole class teaching. The results of the children's subjective survey supported this finding, with significant differences between reported hearing and annoyance of speech sources for large and limited units, and significant differences in perceived ability to hear the teacher (during noisy adjacent activities), and peers (child answering the teacher).

The investigation into sound absorbent finishes and reverberation times suggests that reverberation time criteria given in Danish[5] and Swedish[6] guidance (0.4 seconds) is more appropriate than BB93 criteria (0.6-0.8 seconds) for open plan classbases, in order to maximise ambient STI (in unoccupied conditions). This can practically be achieved in furnished single height semi-open plan units with continuous sound absorbent ceilings. A continuous sound absorbent ceiling also helps to attenuate speech transmission from adjacent units, lowering intrusive noise levels, and minimizing the inevitable reduction in speech-to-noise ratio that typically occurs in occupied conditions.

However coordination of adjacent teaching activities and classroom management strategies are equally important[7], as demonstrated by the reported STI results detailed for each activity and position in the classbase. Other factors to control noise transmission, such as sound attenuation between classbases and classbase layout, are also essential to achieve BB93 compliance[7].

## 4. ACKNOWLEDGMENTS

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