SPEECH INTELLIGIBILITY MEASUREMENTS IN OPEN PLAN CLASSROOMS

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1 INTRODUCTION

Measurements of speech intelligibility and other room acoustic parameters have been carried out in 44 existing semi-open plan primary school classrooms. One of the objectives of the study was to develop a suitable measurement procedure for STI in open plan classrooms in line with BS 60268-16[1], in order to compare acoustic conditions with the performance standards set out in Building Bulletin 93 (BB93)[2].

This paper focuses on the STI measurement procedure and discusses the factors influencing the accuracy of speech intelligibility measurements. Other predictors of speech intelligibility are also considered such as speech-to-noise ratios, RASTI and Speech Interference Level (SIL), in order to explore their use as a predictor of STI and hence speech intelligibility in open plan classrooms.

2 OPEN PLAN CLASSROOMS

2.1 Current building stock

The current building stock of open plan classrooms in UK primary schools consists largely of a mixture of the 'Plowden' classrooms of the 1960s and 1970s, which aimed to facilitate individualised pupil centred learning methods; and the 'Post-Plowden' classrooms of the 1990s, which aimed to facilitate a hybrid of both individualised and whole-class (traditional) teaching techniques.

The trend peaked in 1976 when 10% of all UK primary schools were based on open plan design[1]. Following the introduction of the National Curriculum in 1988, whole class and more traditional teaching methods were widely adopted which resulted in a clash between pedagogy and existing classroom design. As a result, many of the fully open plan Plowden-style classrooms sought remedial treatment to achieve a semi-open design with teaching spaces defined by walls with restricted openings to limit noise transfer. New semi-open 'Post-Plowden' classrooms were also built at this time to accommodate the 'hybrid' approach to teaching in the 1990s, which aimed to combine both styles of learning by increasing the size of the main 'classbase' area to accommodate whole class teaching. Flexible open plan designs were also used with moveable partitions which afforded more acoustic privacy.

Britain is currently undergoing the largest programme in educational reform and school building investment since the Victorian era[3], with Government investment programmes such as 'Building Schools for the Future' and new City Academies. Open planning is a strong element in some new school designs to achieve flexibility, a key requirement of most design briefs for new schools.

2.2 Standards and guidance

Since 2003 schools have been included within the scope of the Building Regulations, with mandatory acoustic performance standards for teaching spaces as set out in Section 1 of Building Bulletin 93 (BB93)[2]. These performance standards include ambient noise level, reverberation time and sound insulation criteria. Good speech intelligibility in open plan classrooms cannot be guaranteed using the usual criteria for cellular classrooms, due to the complex layout of the room and higher intrusive noise levels from adjacent teaching areas. Instead, BB93[2] requires a computer model of the classroom to predict the speech transmission index (STI) in the classroom, based on a specific open plan layout and activity plan. The BB93 criterion for speech intelligibility in an open plan classroom is STI > 0.6, corresponding to ‘Good’ subjective speech intelligibility. This criterion should be achieved for teacher/pupil, pupil/teacher and pupil/pupil communication situations. For the purposes of this paper only teacher/pupil communication is considered.

In addition to this, BB93 sets out a maximum mid-frequency reverberation time in open plan teaching areas of T_{mf} 0.8 seconds. For primary school classbases, the maximum T_{mf} value is 0.6 seconds. The mid frequency reverberation time T_{mf} is the arithmetic average of the reverberation time in the 500, 1k and 2 kHz octave bands, measured for the unoccupied and unfurnished classroom. For this study, reverberation times were measured with classrooms unoccupied but with furniture and fittings in place ($T_{mf,\ furnished}$). Analysis of preliminary data[7] found that for optimum conditions in semi open plan classrooms, reverberation times should not exceed $T_{mf,\ furnished}$ 0.4 seconds.

Although open plan classrooms are expected to be highly flexible in terms of the room layout and teaching activity, a degree of planning and organisation is always necessary for the classrooms to operate successfully. The guidance in BB93 refers to an expected ‘open plan layout’ in order to determine teacher (source) positions and seating plans, and an ‘activity plan’ to determine the type of teaching activity occurring at any one time (whole class address, discussion work, circulation, operation of equipment etc).

3 MEASUREMENT PROCEDURE

Careful consideration must be given to the activity plan and open plan layout in order to make representative and meaningful speech intelligibility measurements. The measurement procedure described in this section was determined from general observations made in existing classrooms. However the client and designer must work together to ensure that the design accommodates (as far as possible) the envisaged organisational plan, and that the client has an understanding of any combinations of activities that the design cannot accommodate, so that the building is acoustically ‘fit for purpose’.

In the UK the combination of whole class instruction and individualised learning (as described in Section 2.1) is commonly seen in the primary school years, with group work activities occurring far less often[4,5]. The more successful open plan classroom designs tend to limit the number of pupils sharing an open space. Teachers generally co-ordinate teaching activities so that conflicts do not occur between adjacent classrooms. Whole class teaching often takes the form of ‘mat’ work on a carpet area with the whole class gathered closely around the teacher. When the class is seated at tables, individualized or group learning often takes place. During this time, teachers tend to walk around the room to give instruction, either one-on-one or to a small group, with relatively short communication distances. If the teacher needs to address the whole class whilst they are involved in this type of task, they will often use a visual signal, rather than raise their voice, to capture the children’s attention before speaking.

The most common categories of classroom activity (relating to noise) were identified for a previous research study[6] as follows:

1. ‘Silent reading or test’ - not relevant here as this activity does not involve speech communication.
2. ‘One person speaking at any one time’ – whole class instruction with rest of the class quiet and listening to the person talking. Generally takes place on carpet with class closely gathered round teacher, but could involve teacher addressing whole class seated at tables.
3. ‘Individual work at tables’ – independent work with some talking. Teacher gives one-to-one instruction during these periods (involving much shorter communication distances).

4. 'Individual work with movement' – as above, involving practical work with movement around classroom to access resources and materials
5. 'Group work at tables' – small group interaction with pupil discussion. Teacher walks around room to communicate to each small group.
6. 'Group work movement' – as above, often involving practical work with movement.

Given the above observations, possible combinations of activities occurring in open plan classrooms are shown in Table 1, where 'critical listening' situations are highlighted. The 'best' and 'worst' case situations are also indicated. For non-critical listening situations, the main design issue is to control noise levels in order to avoid distraction and annoyance rather than achieving high levels of speech intelligibility. This issue has been investigated previously[7] and will not be discussed in this paper.

Table 1: Speech communication situations in open plan primary school classrooms

		Adjacent classbases: dominant activity		
		Whole class	Work at tables	Work at tables with movement
Main classbase activity	Whole class	Coordinated activities (best case)	Uncoordinated activities	Uncoordinated activities (worst case)
	Individual or group work	Non critical – main issue here is control of noise levels to avoid distraction and annoyance (discussed in reference 7)		

On this basis, the following procedure for speech intelligibility measurements in open plan classrooms has been designed with critical listening situations and teacher/student communication in mind.

3.1 Measurement theory

In short, STI is based on the modulation transfer function, m(*F*), which is obtained for 14 third octave modulation frequencies (selected according to the modulation frequencies present in a typical speech spectrum[8]), and seven octave bands from 125 Hz to 8 kHz, to form a matrix of 98 data points. Each value in the matrix can be determined from two independent measurements; the noiseless room impulse response, and the signal-to-noise ratio at the receiver point. The m(*F*) values are interpreted in terms of an 'apparent signal-to-noise ratio', which is irrespective of the actual sources of disturbance (reverberation and/or noise)[1].

According to STI theory, normalised apparent speech-to-noise ratios in the range -15 dB to +15 dB are linearly related to the Transmission Index, TI[1]. Apparent speech-to-noise ratios outside this range are truncated to +15 dB or -15 dB as appropriate, forming a plateau in TI. The TI is obtained by averaging the m(*F*) values in each octave band. Each TI value is weighted according to the band's contribution to speech intelligibility to achieve STI, a dimensionless quantity between 0 and 1.

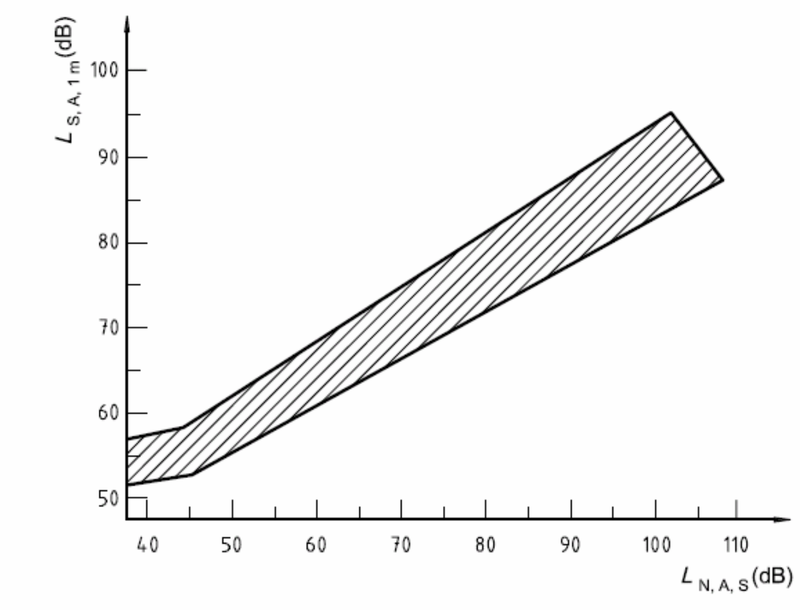
All room acoustic parameters were measured using the WinMLS 2004 software analyser, which uses a deterministic pseudo-random maximum length sequence signal (MLS) for excitation. The average spectrum and level distribution of speech is represented in the test signal by shaping the MLS signal using a filter. The system response of the room is digitally recorded using the PC's own processor and a high quality soundcard. Using the autocorrelation properties of the MLS signal, a Hadamard transformation is performed to obtain the noiseless room impulse response. This measurement method is much faster and more flexible since only one WinMLS measurement needs to be performed at each position (for which a range of speech-to-noise conditions exist). From this, the STI/RASTI value can be calculated by correcting for the actual speech-to-noise ratio achieved in various conditions during post processing. There is no need to simulate occupancy noise directly in the measurement, which can be time consuming and often inaccurate.

3.2 Source level

BB93 states that the average sound pressure levels defined in ANSI 3.5: (1997)[9] for raised voice effort (66.5 dB(A)) should be assumed for teacher-to-student communication, for both male and female talkers. This standard gives octave band sound pressure levels for raised voice at a distance of 1 m in front of the speaker's lips in the free field.

It should be noted that the scope of ANSI 3.5[9] is limited to natural speech in quiet conditions, averaged across a group of talkers and a group of listeners of both genders. Setting the speech spectrum to an absolute level in accordance with BB93 does not account for the Lombard Reflex (the observed effect of people subconsciously raising their speech levels in increasing levels of background noise). Studies have observed an increase in voice level of 0.3 dB per dB increase in noise level for normal communication conditions[10], increasing to 0.5 dB per dB increase for critical communication situations including teaching[11,13]. More recent studies into classroom acoustics have supported this[14]. BS EN ISO 9921[16] demonstrates a variable range of expected vocal effort level according to the Lombard Effect as shown in Figure 1. The precise vocal effort used depends on the talker and the type of communication situation.

Figure 1: Range of vocal effort ($L_{S,A,1m}$) for ambient noise level ($L_{N,A,S}$)[16]



A higher vocal effort would probably be necessary when noise levels exceed around 70 dB, which is likely to occur in an occupied classroom whilst individual work activities with movement are taking place[6]. In one recent study[15] 36 teachers' voice levels were measured in real classroom conditions using a noise badge fixed approximately 20 cm from the teacher's mouth, in order to eliminate background noise as far as possible. The measurements implied voice levels ranging from 63 to 80 dB(A) at 1 m, with an average level of 72 dB(A) at 1 m.

Nevertheless, it is important to protect teachers against the risk of vocal strain for extended periods, resulting in vocal fatigue and voice disorders, found to be a significant problem amongst the teaching profession[14]. In order to evaluate the quality of speech 'communicability', ISO 9921[16] gives an assessment for various vocal efforts shown in Table 2. A raised vocal effort of 66 dB(A) is considered to be 'Good'. Other studies[14] recommend a vocal effort of 60 dB(A) at 2 m in classrooms for 'acceptable' conditions. This is consistent with around 66 dB(A) at 1m, if the decrease in speech level is assumed to be 6 dB per doubling of distance (valid for indoor classroom conditions up to 8 m according to BS EN ISO 9921[16]). In view of this, a 'raised' vocal effort of 66.5 dB(A) at 1 m is an appropriate compromise between achieving the necessary voice level required for speech intelligibility and minimising the risk to teacher's health, and is deemed acceptable for purposes of this study (e.g. teacher-to-student critical communication with main class quiet and listening to the teacher).

Table 2: ISO 9921[16] assessment of speech communication quality

Vocal effort	L_{Aeq} of speech signal at 1m from speaker's mouth, $L_{S, A, 1m}$ (dB)	ISO 9921-1 Assessment
Maximum shout	90	Insufficient
Shout	84	Unsatisfactory
Very Loud	78	Sufficient
Loud	72	Satisfactory
Raised	66	Good
Normal	60	Very Good
Relaxed	64	Excellent

For STI measurements, the overall L_{Aeq} level of the test signal was set to 66.5 dB(A) at 1m from the source in accordance with BS 60268-16[1]. This standard states that a check should be carried out to ensure that the test signal spectrum is correct to within ± 1 dB over the range 88 Hz to 11.3 k Hz, and to 'adjust the equalization (if any) of the test loudspeaker, as necessary, to satisfy this requirement'[1]. Although equalisation was not applied in the measurement chain, a correction was applied where necessary during post processing, when manually entering data for the speech spectrum, to account for this.

3.3 Source directivity

In order to assess the intelligibility of unamplified talkers, the directivity of the source must approximate that of the human head/mouth. BS 60268-16[1] recommends a mouth simulator conforming to ITU-T Recommendation P.51[17] for the highest accuracy. This document specifies the acoustical and electrical characteristics of a sound source at 25 mm from the lip ring and for this reason is mainly used for testing telephone mouthpieces or similar communication networks. Typical source/receiver distances in a classroom range from 1 to 8 m and it is uncertain whether a mouth simulator conforming to ITU p.51[17] would generate an accurate sound field for receiver positions in this range. In order to improve the accuracy of results other studies have recommend use of a combined head and torso simulator conforming to ITU-T recommendation p.58[19].

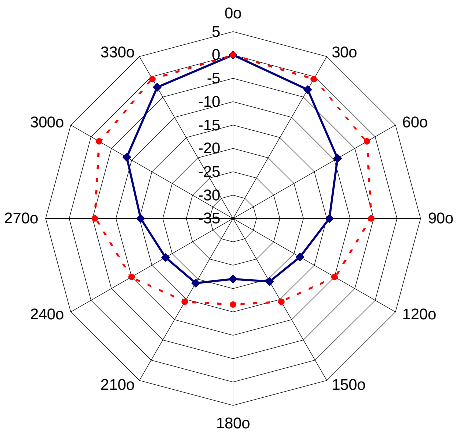
As an alternative, BS EN 60268-16[1] describes a small single source, high quality loudspeaker with a cone diameter not exceeding 100 mm, with a cabinet approximating the dimensions of the human head. A typical head-sized loudspeaker becomes too directional at high frequencies, resulting in an over-estimation of STI. Although using a single cone device is preferable for more accurately replicating a point source, studies have shown that using an additional small tweeter is beneficial as this reduces the directionality at high frequency[18].

Laboratory investigations were carried out to determine the accuracy of a small dual source high quality loudspeaker, with a main cone of 100 mm diameter and a tweeter of approximately 30 mm diameter. The loudspeaker cabinet was well sealed by heavy metal casing and measured 210 x 145 x 115 mm, in line with the approximate dimensions of the human head.

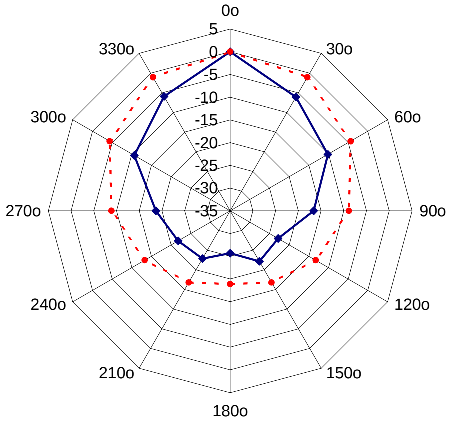
The directional response pattern of the ASC loudspeaker at 1 m was measured in anechoic conditions around the horizontal plane in steps of 30º in free field conditions, in accordance with BS EN 60268-5:2003[20]. The directivity level in decibels was measured at each rotation position relative to the on axis (0°) position and compared with average data measured for the human voice in anechoic conditions[21]. Measured directivity levels were consistent with those of an average human talker at lower frequencies, but became too directional at higher frequencies, as expected.

Figure 2 shows directionality measurements made at 4 kHz and 8 kHz. Within ±30° of the on axis source position, a significant difference (>3 dB) occurred between measured and average voice data. Within ±60° of the on axis position, the significant difference occurred at 1 kHz and above.

Figure 2: Directivity levels for test loudspeaker (——) and average human voice (– –)



4 kHz



8 kHz

An investigation was carried out to examine whether differences in the test source directionality would have a significant effect on STI results. The performance of the head sized test loudspeaker was compared with a GRAS-44A mouth simulator complying with ITU-T P.51[17]. STI was measured for six receiver positions in a classroom environment for both on axis (within ±30º of the source position) and off axis positions (within ±30-60º of the source position) as indicated in Table 3.

The tests showed that use of the head sized loudspeaker resulted in an over-estimation of STI as expected. However this error was generally no more than the typical standard deviation of STI for measurements at a fixed position under steady conditions (0.02 STI)[1], and usually smaller than the just noticeable difference (JND) for STI of 0.03[22].

On the basis of these results, the head sized loudspeaker was used as a test source in the measurement procedure. During measurements, the test source was directed into the centre of the student group, in accordance with BB93[2].

Table 3: STI results using mouth simulator and test loudspeaker

Measurement position	Mouth simulator	Loudspeaker	Difference
S1R1 (on)	0.72	0.73	0.01
S1R2 (off)	0.66	0.68	0.02
S1R3 (off)	0.66	0.68	0.02
S1R4 (off)	0.65	0.70	0.05
S1R5 (on)	0.72	0.71	0.01
S1R6 (on)	0.69	0.71	0.02
Mean	0.68	0.70	0.02

3.4 Effect of occupancy

Increasing background noise reduces the speech-to-noise ratio and hence STI. BB93[2] assumes that the background noise level is the overall noise level due to all teaching and study activities in the open plan space. This may be split into two parts; the intrusive noise level (from adjacent classbases plus ambient noise level), and the noise from the occupants in the main classbase itself (excluding the teacher's voice). In practice, the teacher's voice is likely to be a dominant noise source for the latter, therefore it is very difficult to obtain accurate measurements of noise when the main classbase is occupied without causing significant disruption to normal teaching routine.

However, if the occupants within the main classbase are assumed to be quiet and listening to the teacher (i.e. engaged in a critical listening activity), the intrusive noise level is likely to be dominant, especially when adjacent activities are uncoordinated. Therefore the intrusive noise level alone was measured during the survey, with the main classbase unoccupied, and the effect of occupancy noise was accounted for separately during post processing (as described in Section 3.4.2).

3.4.1 Intrusive noise level

The intrusive noise level was measured using a hand held sound level meter in three main positions in each classroom: at the back of the classroom near the opening (worst case), in the middle of the room; and at the front within 2 m of the teacher's usual speaking position (best case). The dominant activity occurring in adjacent classrooms during the measurement period was recorded using the classroom activity categories described in Section 2.3.

The equivalent continuous noise level parameter was used to describe the intrusive noise level. Both octave band L_{eq} (125 Hz – 8 kHz) and overall L_{Aeq} levels were recorded. The L_{eq} was used to measure intrusive noise in BB93 case studies[2]. Furthermore noise surveys of office environments found the L_{eq} to be highly correlated to subjective auditory sensation[23]. Whereas many surveys have used a long term averaged (L_{eq}) noise spectrum to account for the effect of occupancy noise on STI[2], it is also important to consider the fluctuation in STI with time (this varies with the type of teaching activity and with general fluctuation of noise).

It should be noted that the study of noise in office environments[23] found L_{np} (noise pollution level) to be best correlated to subjective response. This descriptor takes into account the standard deviation of the noise level distribution. More recently, Mapp[18] supported this view by suggesting use of a statistical parameter L_n to account more accurately for the effect of background noise on speech intelligibility.

Variation in noise level was accounted for in the current study by using a short two minute measurement period, and calculating the STI for each noise sample obtained. This method was considered to provide accurate information about how the STI fluctuates with noise and teaching activity, rather than using an average of the measured samples. Previous studies have shown that this method gives a good indication of the fluctuations of noise within a classroom, and does not appear to interfere with teaching or children's concentration[6]. Pilot studies also showed that this period is usually short enough to capture a single activity type before the dominant activity in adjacent classrooms changes.

3.4.2 Main class base occupancy

In order to assess the effect of main classbase occupancy noise using a controlled method, a standard spectrum for occupied classroom noise (42 dB(A) overall) was added to the measured intrusive noise level. This total background noise level was used to correct unoccupied STI results during post processing. The spectrum was based on a published measured octave band spectrum[24], for children quiet in a classroom, normalised to the UK national average class size for primary schools (26 children[25]).

Occupancy also increases the absorption area in a classroom and hence decreases reverberation time. This will in turn have an effect on STI. However a study by Mapp[18] showed that for most positions, increased absorption due to room occupancy does not affect the STI significantly.

3.5 Measurement parameters

3.5.1 Speech-to-noise ratio

Speech-to-noise ratios were calculated from the measured test signal level and noise level at the receiver position. The A-weighted speech-to-noise ratio, S/N(A) was calculated from the measured overall L_{Aeq} values. The weighted speech-to-noise ratio, S/N_w was calculated from the measured octave band L_{eq} values by weighting the speech-to-noise ratio in each octave band according to the band's contribution to speech intelligibility to obtain a single figure value. The weighting factors w_k shown in Table 4 were derived by Houtgast and Steenken[8] after the Articulation index (AI) calculation scheme.

Table 4: Weighting network for S/N_w

Octave band centre frequency (Hz)	125	250	500	1k	2k	4k	8k
w_k	0.13	0.14	0.11	0.12	0.19	0.17	0.14

3.5.2 STI

STI measurements were obtained for the unoccupied classroom as described in Section 3.1 and in accordance with BB93[2] and BS 60268-16[1] using WinMLS. Noise was accounted for during post processing as described in Section 3.4. The head sized loudspeaker described in Section 3.3 was used as the test source, facing into the centre of the student group, in accordance with BB93[2].

Source and receiver positions were arranged to represent the typical use of the classroom by teachers and children, in accordance with BB93[2]. The source position was located at points most frequently used by the teacher for addressing the whole class e.g. in front of the main writing board. A height of 1.65 m was used for the source position. Receiver positions were chosen to represent the range of seating available to the children, at a height of 1.0 m.

3.5.3 RASTI

The room acoustics speech transmission index (RASTI) is a simplified version of the STI method, which uses only two octave bands (500 Hz and 2 KHz) for analysis. This method does not take account of irregularities in the background noise spectrum. However it is considered to be useful for most person-to-person communications in room acoustic applications[1]. WinMLS was used to calculate RASTI, to compare the accuracy of RASTI as a predictor of STI for classroom applications.

3.5.4 Speech interference level (SIL)

The speech interference level (SIL) is a simple method to assess speech intelligibility in a direct communication situation in noise, using a speech-to-noise ratio parameter[16]. The SIL is determined by the difference between the overall A-weighted speech signal level ($L_{S,A,L}$) and the speech interference level of noise (L_{SIL}) at the listener's position. L_{SIL} is determined by the arithmetic average of the sound-pressure levels of the L_{eq} noise level in the 500, 1k, 2k and 4 kHz octave bands. BS EN ISO 9921[16] gives a five point scale subjective assessment for the ratings of both SIL and STI, as presented in Table 5.

Table 5: BS EN ISO 9921 assessment of SIL and STI parameters

BS EN ISO 9921 Intelligibility rating	STI	SIL
Excellent	>0.75	21
Good	0.60 – 0.75	15-21
Fair	0.45-0.60	10 -15
Poor	0.30 – 0.45	3 - 10
Bad	< 0.30	< 3

4 SURVEY RESULTS AND DISCUSSION

This section focuses on survey results which are pertinent to the accuracy of the measurement procedure, and the discussion is restricted to this basis. The measurement parameters used in this study are relevant for persons of a normal hearing capacity in a direct communication situation. Listeners of a second language would require a 4-5 dB improvement in the speech-to-noise ratio for equivalent speech intelligibility, which equates to an increase of the STI of 0.13, or 4 dB SIL[16]. This could also apply to children with additional learning needs.

4.1 STI/RASTI

Mean STI and RASTI results for each intrusive activity are shown in Table 6, for the main classbase unoccupied. The standard deviation is included since the mean results alone are not sufficient to describe the large degree of variation in STI/RASTI with noise.

As expected, 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 (i.e. further away from the speech source and nearer to the noise source). Significant negative correlation was found between STI and activity category (rho = -0.47, n = 508, p < 0.001), and between STI and position (rho = -0.46, n= 475, p < 0.001). This highlights the importance of noting the specific teaching conditions in adjacent classbases and the open plan layout, as this has a significant impact on the noise level and corresponding intelligibility.

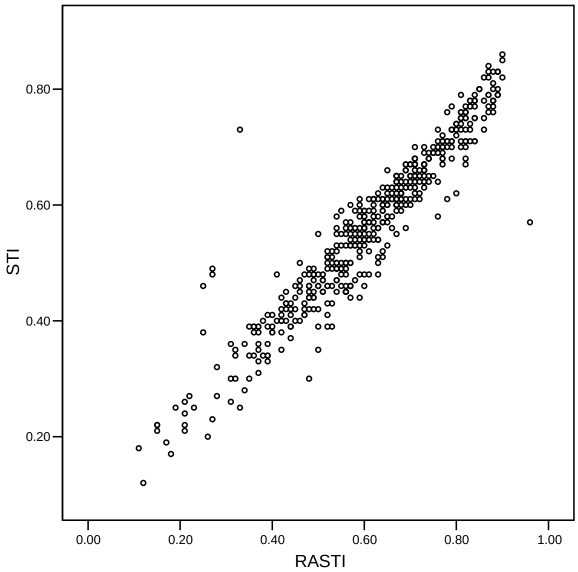
Table 6: Average STI/RASTI for activity and position

Adjacent activity	Position	n	Mean unoccupied STI (σ)	Mean unoccupied RASTI (σ)
One person talking	Front	30	0.75 (0.07)	0.80 (0.12)
	Middle	35	0.71 (0.07)	0.78 (0.07)
	Back	68	0.61 (0.09)	0.68 (0.09)
Individual work at tables	Front	53	0.62 (0.16)	0.66 (0.21)
	Middle	59	0.61 (0.11)	0.68 (0.12)
	Back	156	0.50 (0.12)	0.54 (0.14)
Individual work with movement	Front	9	0.62 (0.09)	0.68 (0.08)
	Middle	13	0.51 (0.10)	0.54 (0.11)
	Back	39	0.46 (0.11)	0.50 (0.13)

The correlation between RASTI and activity (rho = -0.47, n = 506, $p < 0.001$) and RASTI and position (rho = -0.43, n = 473, $p < 0.001$) was similar to that for STI results. Figure 3 shows the relationship between STI and RASTI. Although the correlation between STI and RASTI was very strong (r= 0.95; n = 501; $p < 0.001$), the mean results for RASTI were significantly higher than STI results by 0.04-0.06, depending on the type of activity and position.

In the case of the RASTI measurements, the effective speech-to-noise ratio is generally over-estimated, since only two octave bands (500 Hz and 2 kHz) are used for analysis. Use of RASTI to assess for the BB93 criterion for open plan classrooms would indicate BB93 compliance in some cases where the equivalent STI rating would not. Inspection of the best fit line and 95% confidence intervals indicates that a RASTI value of at between 0.65 and 0.75 corresponds to an STI value of 0.6. Therefore a RASTI value of at least 0.75 should be achieved to ensure compliance with BB93.

Figure 3: Scatterplot of STI and RASTI



The reduction in STI due to the addition of main classbase occupancy noise is shown in Table 7. The estimated STI falls by 0.02 - 0.05 when noise due to occupants within the main class is taken into account. There is a greater difference between unoccupied and occupied results for quieter activities, and for positions at the front of the classroom, since intrusive noise levels are lower for these situations, and the occupied noise level would make a greater contribution to the total background noise level (occupied plus intrusive noise level). For positions at the back of the room and for noisier adjacent activities, the intrusive noise level is dominant and hence a smaller difference occurs between the occupied and unoccupied STI results.

Table 7: Reduction in STI due to main classbase occupancy noise

Adjacent activity	Position	n	Mean reduction in STI due to main classbase occupancy noise
One person talking	Front	30	0.05
	Middle	35	0.05
	Back	67	0.04
Individual work at tables	Front	53	0.03
	Middle	59	0.03
	Back	156	0.02
Individual work with movement	Front	9	0.03
	Middle	13	0.02
	Back	37	0.02

4.2 Speech-to-noise ratios

Figure 4-6 show the relationship between STI and the measured speech-to-noise parameters S/N(A), SIL, and S/N_w respectively. A linear relationship may be assumed up to a certain point before the STI begins to plateau.

Results are split into data for shorter, 'optimum' reverberation times ($T_{mf,\ furnished}$ < 0.4 seconds) and longer reverberation times ($T_{mf,\ furnished}$> 0.4 seconds). The correlation coefficients for each relationship are shown underneath the figures. For longer reverberation times ($T_{mf,\ furnished}$> 0.4 seconds), 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 where the furnished mid-frequency reverberation time is controlled to 0.4 seconds or less, the linear relationship continues to hold for higher speech-to-noise ratios.

The results for S/N(A) and SIL show a very similar relationship and correlation (r = 0.93 for controlled reverberation times) and there appears to be no significant difference in accuracy between S/N(A) and SIL as a predictor of STI. Furthermore, S/N(A) is a simpler parameter to calculate. Inspection of the 95% confidence interval line of best fit for the data shows that whereas at least 21 dB SIL is required to ensure BB93 compliance, the equivalent A-weighted speech-to-noise ratio needed is 13 dB.

The relationship between S/N_w and STI shows a stronger correlation (r = 0.96 for controlled reverberation times), confirming that of the three speech-to-noise parameters, S/N_w is the best predictor of STI. For controlled reverberation times ($T_{mf,\ furnished}$ < 0.4 seconds), a minimum SN_w of at least 8 dB is required to ensure BB93 compliance. For higher reverberation times, the required S/N_w increases to 13 dB.

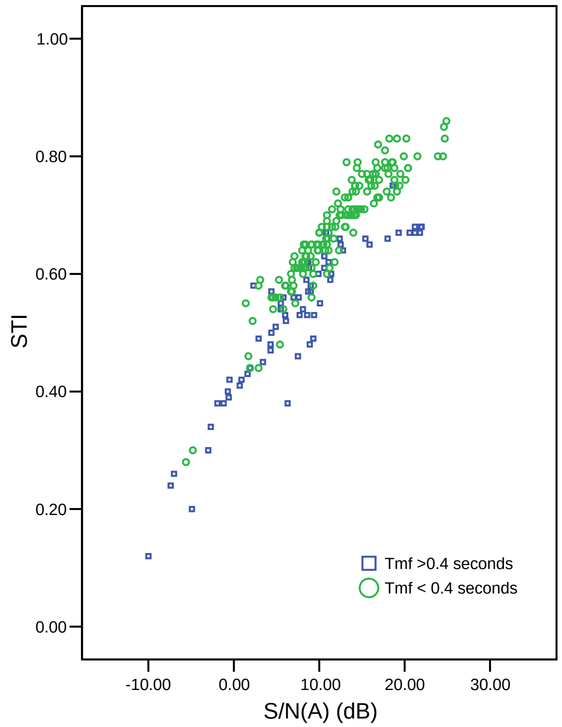
5 CONCLUSIONS

A practical method has been presented for measurement of STI in open plan classrooms. Measurement of STI is a complex procedure requiring specialist equipment which can be expensive. Alternative parameters may be used as a predictor of STI and hence speech intelligibility. Equivalent criteria to ensure BB93 compliance for open plan classrooms for each parameter are summarised in Table 8. Speech-to-noise ratio parameters (SIL, S/N(A) and S/N_w) are more accurate predictors of STI for controlled reverberation times ($T_{mf,\ furnished}$ < 0.4 s). These alternative predictors should be used as an additional tool to assess speech intelligibility rather than as a substitute for STI.

Table 8: Equivalent criteria to achieve BB93 requirement

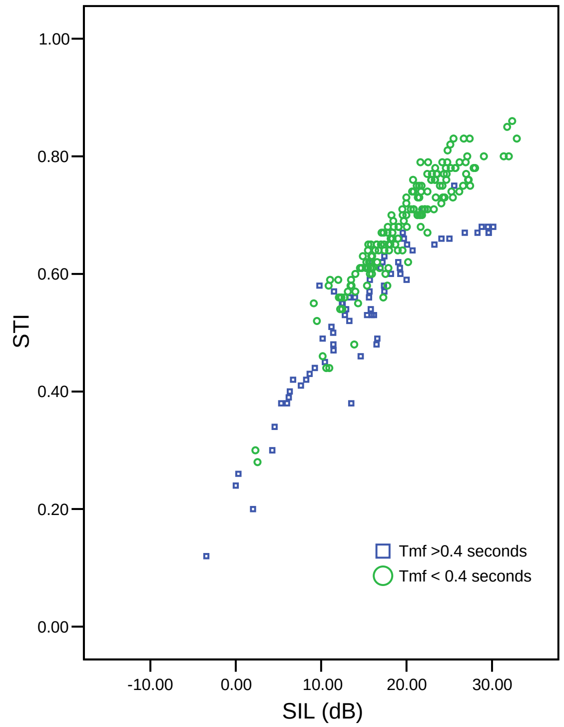
Parameter	Minimum criterion to ensure BB93 compliance (95%confidence interval)
STI	> 0.6
RASTI	> 0.75
SIL	21
S/N(A)	13
S/N_w: controlled RT ($T_{mf,\ furnished}$ < 0.4 s)	8
S/N_w: higher RT ($T_{mf,\ furnished}$ > 0.4 s)	13

Figure 4: STI and S/N(A)



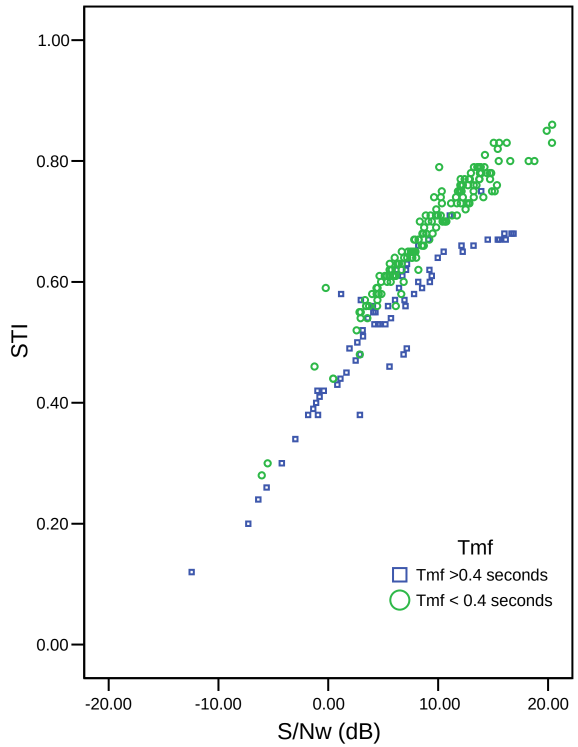
T < 0.4 s: r = 0.93; n = 162; p < 0.001
T > 0.4s; r = 0.91; n = 69; p < 0.001

Figure 5: STI and SIL



T < 0.4 s: r = 0.93; n = 162; p < 0.001
T > 0.4 s: r = 0.90; n = 68; p < 0.001

Figure 6: STI and S/Nw



T < 0.4 s: r = 0.96; n = 162; p < 0.001
T > 0.4 s: r = 0.93; n = 69; p < 0.001

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