A SURVEY OF CLASSROOM ACOUSTICS AND REMEDIAL TREATMENTS

Anne L. Carey — Department of Engineering Systems, London South Bank University, UK
Bridget M. Shield — Department of Engineering Systems, London South Bank University, UK
Julie E. Dockrell — Institute of Education, University of London, UK
Kate Rigby — Institute of Education, University of London, UK

1 INTRODUCTION

A recent project has investigated the effects on children's learning and teachers' health of room acoustics, remedial acoustic treatments and the use of sound field systems in the classroom. As part of the project an extensive survey of room acoustic characteristics of primary school classrooms has been carried out. This work has surveyed both a larger number and broader range of classroom types and ages than earlier studies[1-4], including rooms which have been acoustically treated, untreated rooms, and classrooms in which sound field systems have been installed. This work therefore aims to expand knowledge of the acoustic conditions in the existing classroom stock, how some of these classrooms have been remedially treated and how they compare with current acoustic requirements for new and re-furbished classrooms[5]. It has been suggested[3] that due to the small range in size and acoustic conditions found in classrooms, reverberation time may provide sufficient accuracy as an indicator of potential speech intelligibility. This suggestion is investigated further in this paper and conclusions verified using a larger and more varied sample of classrooms than before.

There is currently a trend among education authorities to overcome listening problems caused by poor acoustics or individuals with listening difficulties in classrooms by installing sound field systems, regardless of the acoustic conditions of the room. Among the classrooms with sound field systems in the survey examples of good and bad practice in their installation and use were found. Based upon these examples, suggestions for guidance in the installation of sound field systems are given. It has been suggested to the authors[6] that there may be a limited number of types of classroom, and that it may be possible to simplify them into a small set of groups with similar attributes. These groups could then be used as a guide as to what to expect acoustically when first considering remedial work on a classroom. The paper will conclude by classifying rooms according to their construction and volume. It is proposed that simplifying the identification of rooms into one of these groups may help in deciding whether rooms are suitable for the installation of sound field systems, or whether they require further acoustic treatment. It will also hopefully show for which type of rooms more expert advice is required. This issue is currently being addressed in the U.S.[6] and is also discussed in Building Bulletin 93[5], but the cautionary advice given does not yet seem to have influenced practice in the U.K..

2 ROOM ACOUSTIC MEASUREMENTS

2.1 Classrooms included in survey

Measurements have been carried out in a total of 55 cellular classrooms in 25 schools. Fifty-three of these were mainstream classrooms and 2 were partial hearing units (PHU). Table 2.1 shows a summary of the rooms that have been measured including information on:

- the number of classrooms with a sound field system (SFS)
- the number of classrooms with acoustic treatment
- the age of the children taught in each of the classrooms

In this instance acoustic treatment refers to any acoustic absorption material on ceilings or on ceiling and sections of wall installed for the purpose of reducing reverberation time and noise. Throughout this paper this term will exclude carpets, curtains and other soft furnishings. A sound field system is a speech reinforcement system used by the teacher in the classroom.

	Untreated	Treatment only	SFS only	SFS and treatment	Treated PHU	TOTAL
Reception (4-5 yrs)	3	1	2	---	1	7
Year 1 (5-6 yrs)	4	---	3	---	---	7
Year 2 (6-7 yrs)	4	1	1	1	---	7
Year 3 (7-8 yrs)	1	1	6	---	---	8
Year 4 (8-9 yrs)	1	1	3	---	---	5
Year 5 (9-10 yrs)	3	---	5	---	1	9
Year 6 (10-11 yrs)	2	---	6	3	---	11
Year 7 (11-12 yrs)	1	---	---	---	---	1
TOTAL	19	4	26	4	2	55

Table 2.1- *Overview of classrooms where acoustic measurements were carried out*

The volume of the measured rooms ranged from 104 m^3 to 372 m^3 (mean 206 m^3) and ceiling heights (measured at the centre of the room) ranged from 2.35 m to 5.4 m (mean 3.5 m). Rooms measured included a wide range of design styles and ages, with the oldest being built in 1850 and the most recent in 2003 (all prior to the introduction of Building Bulletin 93[5]). Table 2.2 shows the age ranges of the rooms measured. The availability of classrooms from the different periods reflects the political and social climates at various times in history, and government attitudes towards school building.

Pre - 1909	1910-1939	1945-1979	1980-1999	Post – 2000
26	3	16	5	5

Table 2.2 – *Year of construction for measured classrooms*

2.1.1 Measurement equipment and method

Unless rooms were very small, measurements were made at six receiver positions with two source positions, giving a maximum of 12 measurements in each room. Source and receiver positions were arranged as far as possible to represent the typical use of the classroom by teachers and children. The source was located at points most frequently used by the teacher for addressing the whole class, e.g. in front of the main writing board, at the teacher's desk etc.. Receiver positions were chosen to represent the range of seating available to the children. Source and receiver heights were set at 1.6 and 1.2 m respectively as recommended in BB93 and both were mounted on secure stands to prevent movement during measurement. All parameters were measured using either MLSSA or WinMLS analysers and an omni-directional source and receiver. Originally it was planned that the MLSSA analyser would be used for all measurements. However, the hardware proved to be bulky and impractical, was sometimes unstable (due to its age) and has also been shown to be unreliable in tests of reproducibility[8,9]. It was therefore decided to change to the WinMLS system. Using a high quality laptop with a professional soundcard WinMLS proved to be more stable, reliable and easier to use than MLSSA. WinMLS also provides a log-sine sweep for excitation which has been shown to have higher immunity to noise during measurement[9].

Over recent years there has been much debate on the types of source and receiver which should be used for room acoustic measurement[3,10,11]. Although all the arguments have not been fully resolved, current thinking is tending towards the use of an omni-directional microphones and directional loudspeakers[9]. The use of omni-directional source and receivers for the room acoustic measurements in this project could therefore be questioned. However, BB93 requires the use of BS EN 3382:1997[12] for reverberation time measurement, and since comparison with BB93 was one of the main purposes of this study it was felt that the equipment used was the most appropriate for this work. Working in primary school classrooms also involves limitations on time and practical issues which make the use of more than one source infeasible. Measurements were generally carried out between 7am and 8:30am or 3pm and 7pm and took place in classrooms unoccupied but furnished and decorated as if in normal use. During the project measurements were also carried out in occupied rooms but these results are not be presented here. Background noise measurements ($L_{Aeq,5min}$) were made in most of the classrooms before or after the room acoustic measurements.

2.2 Results

Results for both treated and untreated classrooms appear together in this section. Treated classroom data appears in the graphs in pink, untreated in blue. All data shown is spatially averaged over the 12 measurement positions. Figure 2.1 shows the range of unoccupied mid-frequency reverberation times (T_{mf}) and mid-frequency early decay times (EDT) found in the 55 classrooms. T_{mf} is the parameter used in BB93 for specifying reverberation in classrooms and is equal to the average of the reverberation measured at 500, 1000, and 2000 Hz. The T_{mf}'s shown in Figure 2.1 are measured as T_{30}.

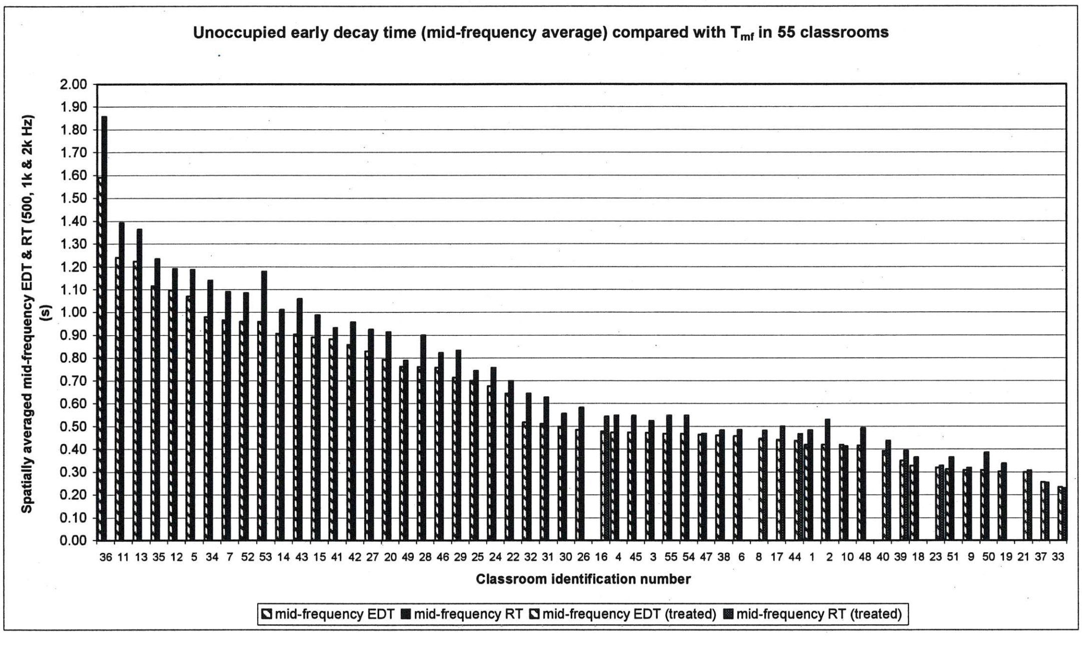

Figure 2.1 - *Mid-frequency EDT compared with T_{mf} in 55 classrooms*

A wide range of reverberation times were found in the 55 classrooms, the lowest being ~ 0.2 s and the highest just over 1.85 s (a range of 1.65 s). Over half of the classrooms measured (29) have mid-frequency reverberation times complying with BB93 reverberation requirements ($T_{mf} \leq 0.6$ s for primary schools). However, rooms were not measured without furniture or fittings as specified in BB93. Measured in an unfurnished state it is highly likely that reverberation times would be longer and fewer classrooms would comply. The 10 acoustically treated classrooms all comply with the BB93 T_{mf} requirement. The mean T_{mf} for the 10 treated classrooms is 0.39 s and for the untreated classrooms is 0.78 s. The longest EDT measured in a classroom is just under 1.6 s and the shortest is 0.23 s. The range for EDT is 3 s smaller than that found for T_{mf}. It can clearly be seen that in classrooms these two parameters are very closely related. This is confirmed by Pearson product moment correlation analysis (r = 0.995, significant at the 0.01% level). In all but three of the classrooms T_{mf} is longer than EDT. The difference between the two parameters appears to increase as their values increase, although there are some exceptions.

Figure 2.2 shows the average reverberation times (T_{30}) in octave bands (125-8000 Hz) of all the classrooms separated into treated and untreated. The solid lines are the mean for all the classrooms and side bars the standard deviation of data from this mean. It can be seen from the graph that in general acoustically treated classrooms maintain lower reverberation times across the whole frequency range than untreated ones. There are however some untreated classrooms which also achieve low reverberation times across the full range of frequencies. Some of the untreated rooms will have low reverberation times because of their small volume. However, there are some classrooms with larger volumes which still maintain low values of T_{mf}, as discussed below.

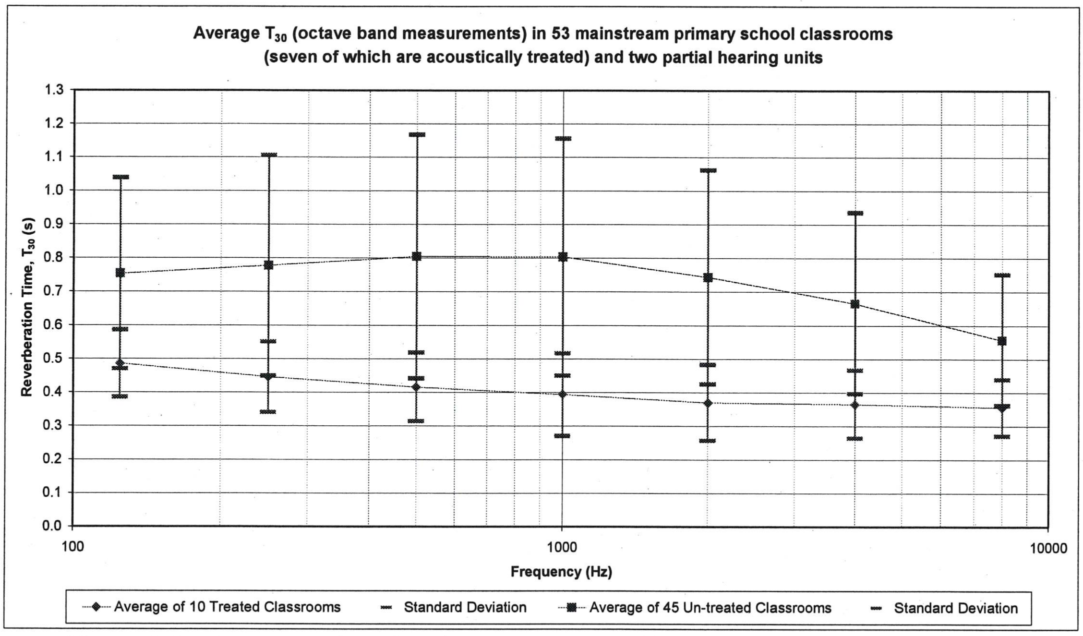

Figure 2.2 - *Average octave band measurements of T_{30}, unoccupied, for 55 classrooms*

Figure 2.3 compares the mid-frequency reverberation times (T_{mf}) measured in the classrooms with their volume. Seven of the untreated rooms with volumes over 225 m^3 have mid-frequency reverberation times under 0.6 s and one room with a volume in excess of 250 m^3 has a very short T_{mf} of just over 0.4 s. Regression lines have been plotted for treated and untreated data separately. Although some of the untreated rooms have short T_{mf}'s the vast majority have times which appear strongly related to their volume. The untreated room regression line has a steeper gradient than the treated, from which it can be extrapolated that even at larger volumes acoustic treatment has the potential to dramatically reduce reverberation.

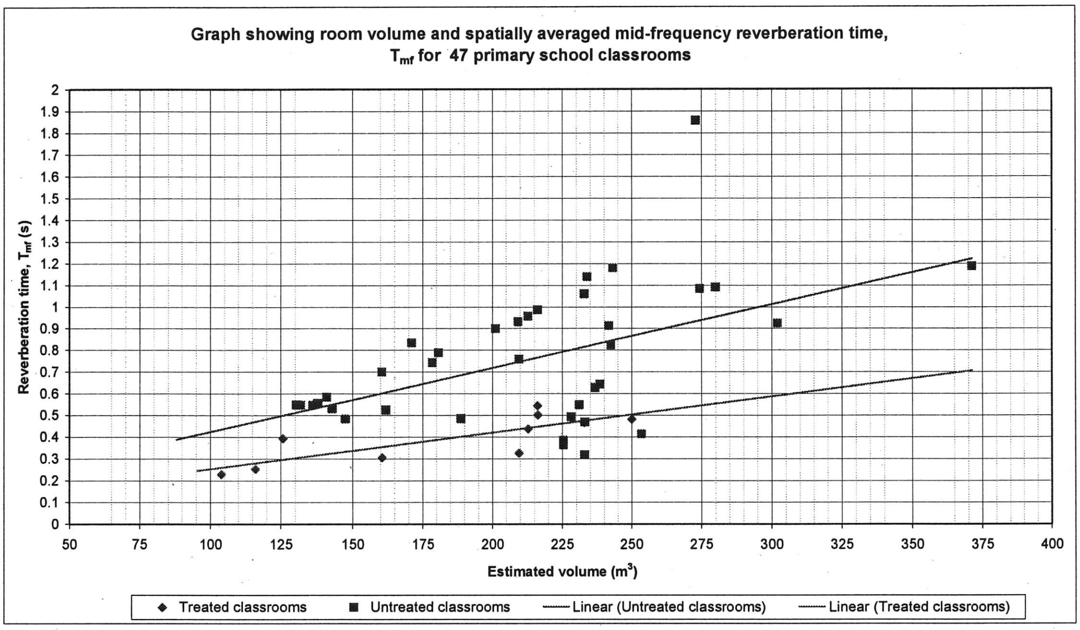

Figure 2.3 - *Classroom volumes compared with mid-frequency reverberation time (s)*

Examples of the improvement in reverberation time which can be achieved from treatment in a classroom can be seen in Figure 2.4. This graph shows the mean and standard deviation for reverberation (T_{30}) for matched classrooms (pairs of rooms which are exactly the same except that one has acoustic treatment and the other does not). From this it can be seen that rooms with long reverberation times can be brought within the BB93 range across all frequencies using appropriate acoustic treatments.

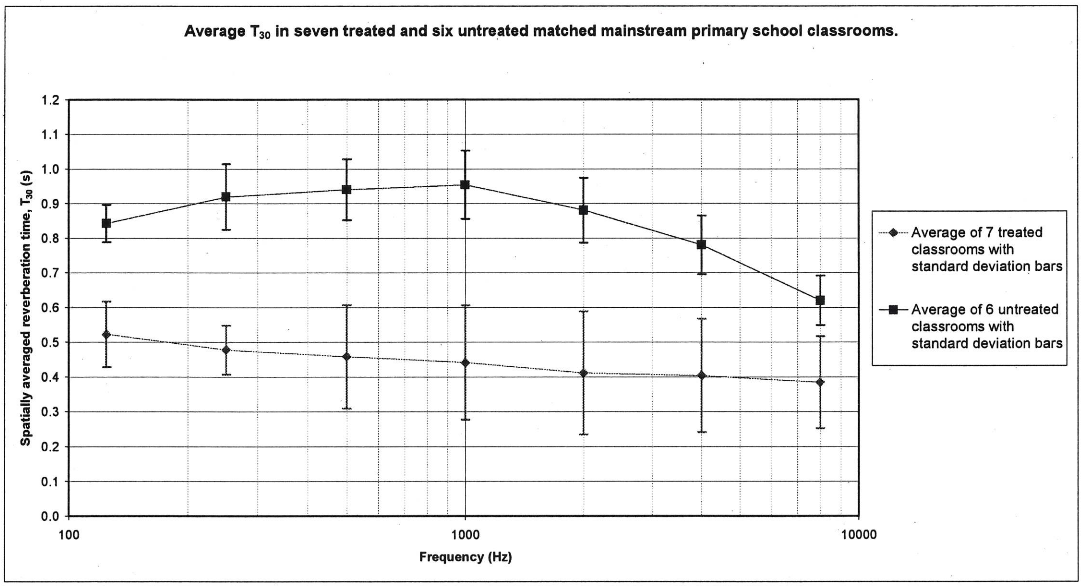

Figure 2.4 - *The affect of acoustic treatment on reverberation time (T_{30}) in seven classrooms*

Figure 2.5 shows the speech transmission index (STI) values that have been measured in the 55 classrooms compared with the mid-frequency reverberation time. The range of STI values measured is from 0.51 to 0.88. Comparing the measured data with the STI subjective scale[13], 6 classrooms were judged "fair", 21 classrooms were judged "good" and 28 classrooms were judged "excellent". All 10 acoustically treated classrooms (shown in pink) are in the "excellent" range.

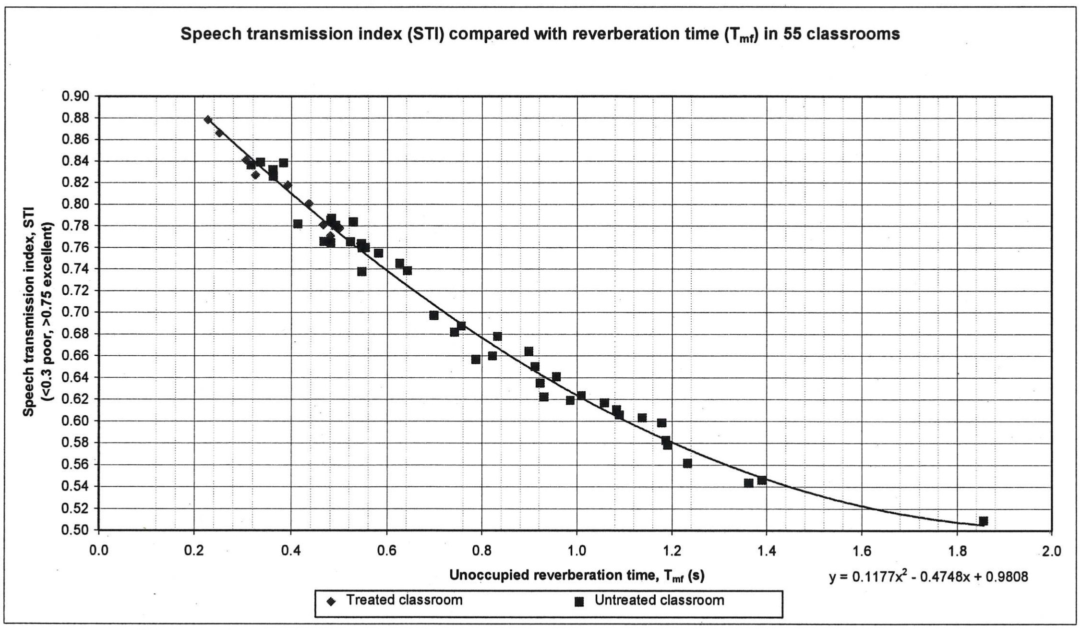

Figure 2.5 - *STI compared with T_{mf} in 55 treated and untreated classrooms*

The regression curve plotted on Figure 2.5 indicates that there is, as was suggested by Mapp[3], a strong relationship between STI and reverberation in classrooms. It appears that if STI is providing an accurate prediction of speech intelligibility in the classrooms (with low background noise) then so is unoccupied T_{mf}. Using this data the range of error in STI when predicted by T_{mf} is around 0.4 and the BB93 requirement of 0.6 s reverberation time corresponds to an STI of 0.75. It should be noted that the use of the omni-directional loudspeaker as source may be resulting in an under estimation of the STI as compared with a dummy head source or small loudspeaker[3]. The unoccupied background noise levels measured in the classrooms ranged from 30 to 45 dB(A) $L_{Aeq,5min}$.

2.3 Discussion

The reverberation time measurements in the 45 untreated classrooms show that even some of those with higher volumes are achieving BB93 requirements (for reverberation) without having specific treatment. Further investigation into the design and layout of these classrooms will be carried out to see how this has been achieved. The classrooms which have been specifically acoustically treated, some of which had fairly high reverberation times before treatment, now all comply with the BB93 requirements for reverberation. It would be interesting to examine the difference in noise levels during lessons following acoustic treatment since there is some disagreement[2,4] as to the effect absorption has on noise levels in the classroom, and therefore whether it is better for intelligibility to reduce reverberation or to increase the speech signal.

The discrepancy between reverberation and early decay times has been noted and in some cases is probably caused by coupled spaces. These parameters will be compared with subjective opinions of the classrooms obtained during a parallel questionnaire survey of children and teachers.

Unlike the reverberation time measurements STI values for the classrooms were found to be not very wide ranging. This is obviously not ideal since subjectively the classrooms were not very similar, and need to be more differentiated by an intelligibility scale to help in assessing need and optimum use of resources. This lack of variation in STI suggests five possibilities:

- primary school classrooms all have very similar speech intelligibilities
- STI is not very sensitive to changes in speech intelligibility in classrooms
- using the omni-directional source has caused a reduction in the range of STI
- the absence of realistic background noise during measurements has reduced the range of STI measured
- the STI scale needs to be re-calibrated in order for it to provide useful information in classrooms.

Further analysis and comparison with subjective speech intelligibility test data should address some of these issues.

3 SOUND FIELD SYSTEMS

3.1 What is a sound field system?

A whole classroom "sound field system" (SFS) is essentially a simple speech reinforcement system used by the teacher. The two most common set-ups in use in the U.K. are the four speaker system, which has the four (or more) small moving coil loudspeakers positioned approximately three-quarters of the way up the wall and aimed so as to cover the whole class, and the column loudspeaker which is placed in one corner of the classroom. There is also a system using flat panel loudspeakers (DML) that can be slotted into false ceilings but this is not as popular as the other two versions at the present time. The systems are usually fairly simple and consist of a boom or collar mounted directional radio microphone and transmitter, a radio microphone receiver, a mixer/amplifier and the loudspeaker/s. The system may also include an additional roaming microphone for use by the pupils. A typical system for a primary school classroom costs £1000 to £1500, although systems are often purchased in bulk, which can considerably decrease the price. It should be noted that acoustic ceiling treatments typically cost three times more than this, depending on how large and complicated the ceiling, and whether the ceiling height will be lowered.

3.2 Why and where are SFS installed?

The aim of the SFS is to provide all children in the room with an equal teacher's speech to noise ratio, rather than having the children situated further away from the teacher struggling to hear. The system level is meant to be set so it provides all the children in the class with around 10-15 dB signal to noise ratio (the optimum for intelligibility[1]) and is not meant to be used to increase the teacher's voice to unrealistic levels. There is a wide range of work, mostly in the U.S., which has investigated the effects of using SFS, but to date very little has been done in Europe. Some examples of claimed results are that SFS's produce academic improvement, increase attention and reduce inappropriate behavior[7]; these issues are currently being investigated further by the authors.

During the project four main drivers for the installation of SFS in U.K. classrooms have been found. The first is the presence of a special listener (a child with hearing difficulties or another special need) in the class; this will cause a parent, school SEN (special educational needs) coordinator, head teacher or a local authority figure (from the Audiology team or SEN services) to request that a SFS be installed. The second is when a room has poor acoustics and teachers are finding it difficult to teach in the space. A head teacher may then contact the LEA buildings division or vice versa and request (if the cash is available) that the poor acoustics be improved. The third is if a teacher has voice problems, in this case a SFS may be installed for the sake of the teacher's voice rather than to necessarily improve the signal strength for the pupils. The fourth reason for SFS being installed is where money is allocated to the LEA for the purpose of improving school buildings, some of which may be earmarked for acoustic refurbishment. Systems may be made available to the schools for any of the above reasons, or the LEA may install systems in a blanket manner, for example in one class in each year in all their primary schools, in order to provide for pupils with a special need. SFS have a fairly evangelical following in the U.S. and this has at some level bled into the U.K. education establishment where there now seems to be a general misconception that SFS's alone can overcome the problems of poor acoustics. Figure 3.1 shows some examples of reverberation times (and some background noise levels) in classrooms with SFS which were included in the acoustic survey. From this it can be seen that SFS have been installed across the whole range of classrooms. In some cases the SFS are installed in rooms in which they may be working well and potentially making a difference. However, some of the rooms in which they are installed have reverberation times and volumes which could very easily be causing problems, and in others it seems highly unlikely that a SFS will improve the situation due to their small size and low background noise levels. The current research by the authors into the benefits of SFS should clarify some of these points.

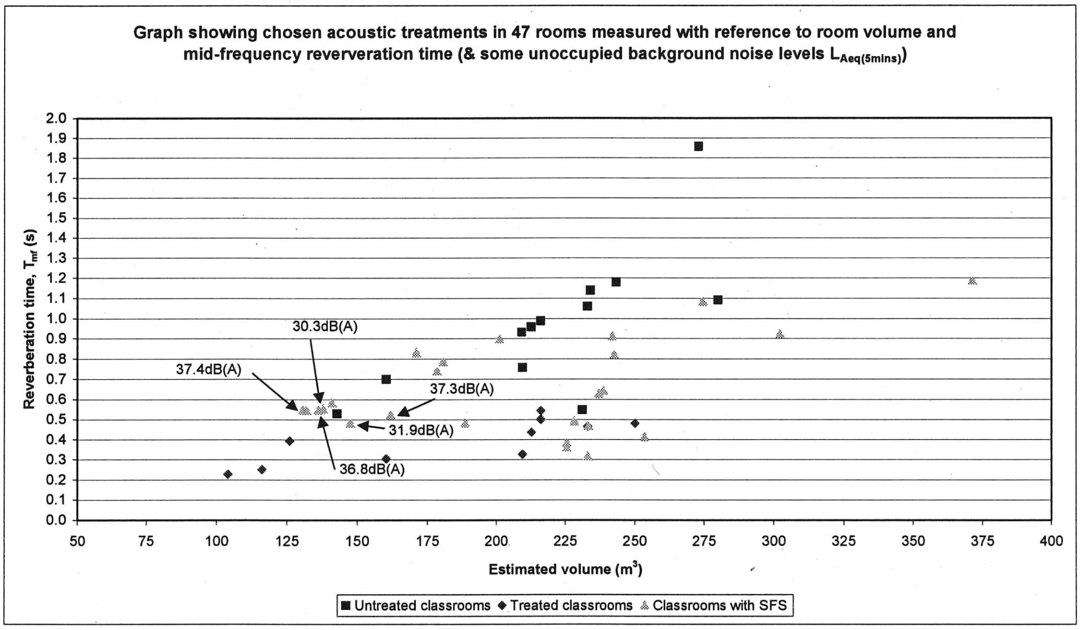

Figure 3.1 - *Reverberation times and a sample of background noise levels in rooms where SFS have been installed*

Incidents of installation in the incorrect rooms seem to have occurred either where LEA's have used a blanket strategy for locating systems, or have installed them for the sole purpose of one child with a special need. The probability of a system being located in an inappropriate room appears to be increased if installation is left up to a third party (these people often have little knowledge of room or electro acoustics). Although the sentiment of 'improving' acoustics for all is admirable, the reality of the SFS in some of these classrooms is that they go unused (either because rooms are too reverberant or so small that the teacher feels it is completely unnecessary) and are therefore a waste of money as no one gets better acoustics. Better perhaps then to spend less on individual systems aimed at improving acoustics for all, and more on treating particular rooms with real acoustical problems. It should be noted that installing SFS in unsuitable rooms is not encouraged by the companies that make the systems, who advise that SFS should not be installed in rooms with incompatible acoustics. However, the decision on whether or where to install systems is usually made by non-acoustic specialists who are unaware of the potential problems.

3.3 Suggested improvements/good practice

Five important questions to ask when considering installing a SFS in a classroom are:

1) Does the classroom have appropriate acoustics for installing a SFS?
2) Where will most of the oral instruction take place in the classroom?
3) Can the loudspeaker type that is being installed provide adequate coverage of this area?
4) Does the teacher understand what the SFS is for, how to use it and who to contact if it's not working?

5) Is there someone enthusiastic in the school willing to take responsibility for looking after the SFS, ensuring adequate training for users and being the main liaison between the teachers and the maintenance/installation people?

It was obvious that in some of the classrooms studied these questions had not been considered, leading to problems with the installation and use of the SFS; in some cases the SFS was not used at all by the teacher. The best installed systems seen during the project were those whose installation had been advised by someone with some acoustic knowledge, and in consultation with the class teacher. The situations where SFS seem to be working best are where heads and teachers are enthusiastic about their use and are willing to find out more about the system and persevere with getting the sound right in their classrooms. Obviously the teachers can only do this if someone has installed the correct system for them in their room and if their room is suitable for a system in the first place. The SFS is not a panacea for all classroom acoustic evils but in the right situation and set up correctly it can probably be of some assistance.

In order to assist head teachers and other non-specialists in assessing classrooms, a classification of rooms may be useful. Figure 3.2 shows an example of a classification system, using a subset of the classrooms which have been measured in this study. This type of classification could be used, alongside other relevant information, to provide guidance to non-specialists on suitable remedial treatments.

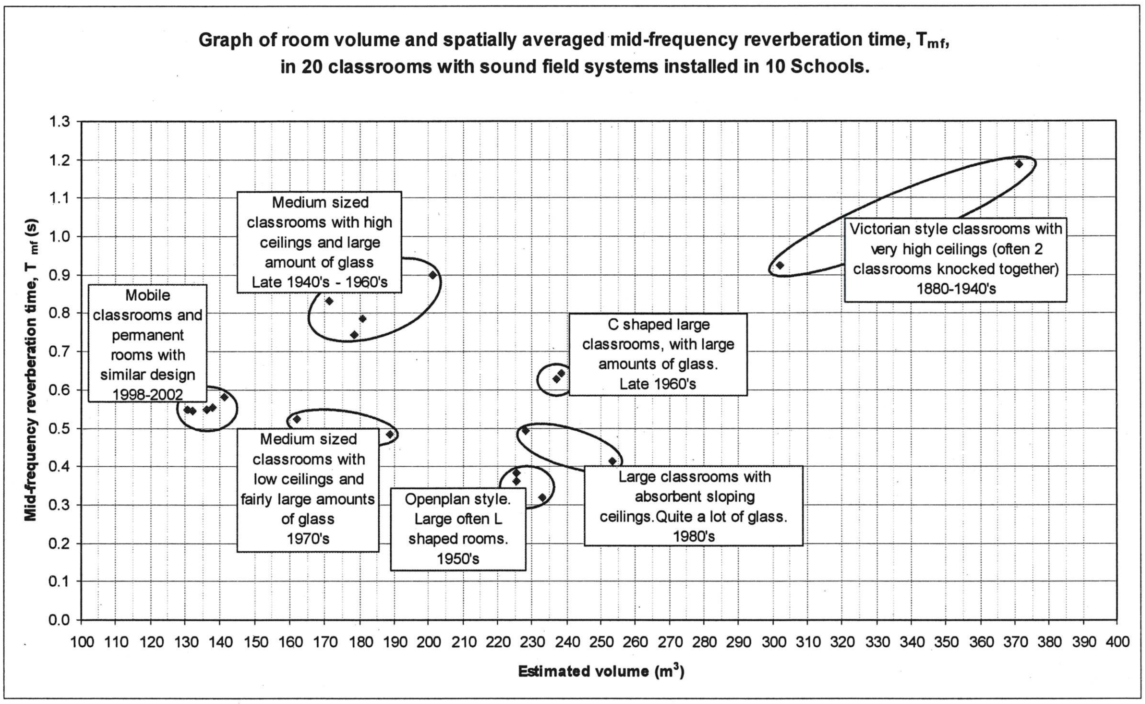

Figure 3.2 – *Classification of classrooms into 7 types using age, reverberation & volume*

4 CONCLUSIONS

An acoustic survey of classrooms has shown wide variation in reverberation times in the rooms measured. However, variation in STI (measured in low noise conditions) did not appear to reflect the range of speech intelligibility across the rooms.

Remedial acoustic treatments have been shown to successfully reduce reverberation times to required values. Interestingly some rooms with large volumes but without specific acoustic treatment also met BB93 reverberation time requirements; further study of these rooms will be made.

In many schools in the U.K. sound field systems are being installed in classrooms without regard to the acoustic conditions of the rooms. In many cases acoustic treatment alone would be the better option. In others, for successful use of sound field systems, it is essential that installation is accompanied by suitable acoustic treatment.

Classrooms fall into a limited number of categories. Classification of rooms into these categories may be useful in advising on the most appropriate method for dealing with unsatisfactory acoustic conditions.

5 ACKNOWLEDGEMENTS

This work has been funded by the Engineering and Physical Sciences Research Council. The authors would like to thank Anastasis Efentakis, formerly of London South Bank University, for his participation in the project.

6 REFERENCES

1. J.S. Bradley, "Speech intelligibility studies in classrooms", *Journal of the Acoustical Society of America*, **80**, pp.846-854, (1986)
2. D.J. MacKenzie and S. Airey, "Classroom Acoustics: A Research Project", *Heriot-Watt University, Summary Report*, (1999)
3. P. Mapp and C. Boyden, "Measuring speech intelligibility in classrooms, with and without hearing assistance", in *Proceedings of the Institute of Acoustics*, **25**, part 7, pp. 156-160, (2003)
4. H. Sato & J.S. Bradley, "Evaluation of acoustical conditions for speech communication in active elementary school classrooms", in *Proceedings of the International Congress on Acoustics*, part II, pp. 1187-1190, (2004)
5. Department for Education and Skills, Building Bulletin 93, "Acoustic Design of Schools", The Stationery Office, 2003, www.teachernet.gov/acoustics, (2003)
6. P. Mapp, Personal communication (2003)
7. C. Crandell, J. Smaldino and C. Flexer, "Sound Field Amplification: Applications to Speech Perception and Classroom Acoustics", 2nd Ed., Thomson Delmar Learning, (2005)
8. J.S. Bradley, "An international comparison of room acoustic measurement systems", *National Research Council of Canada Internal report IRC-IR-714*, (1996)
9. A. James, "Workshop on room acoustics measurement – analysis of comparative measurements", *National Physical Laboratory Report 9558/2*, (2004)
10. P. Mapp, "Speech intelligibility measurement – The current state of the art", in *Proceedings of the Institute of Acoustics*, **25**, part 7, pp. 238-246, (2003)
11. A. James, "Deep study into standards for room and building acoustics", *Technical Report 9506/1, National Physical Laboratory*, National Measurement System Acoustic Metrology Programme, December (2000)
12. British Standard, BS EN 3382:1997, "Measurement of reverberation time of rooms with reference to other acoustical parameters", (1997)
13. H.J.M. Steenken and T. Houtgast, "Validation of the revised STI_r method", *Speech Communication*, **38**, pp.413-425, (2002)