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Inter-Noise 2009 [Proceedings], pp. 1-9, 2009-08-24

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NRCC-51320

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August 2009

A version of this document is published in / Une version de ce document se trouve dans:
Inter-Noise 2009, Ottawa, Ontario, August 24-26, 2009, pp. 1-9

Ottawa, Canada
INTER-NOISE 2009
2009 August 23-26

A New Look at Acoustical Criteria for Classrooms

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ABSTRACT

High quality speech communication is critical to most learning activities in classrooms and speech communication is the most noise-sensitive learning activity. Acoustical criteria for classrooms should therefore optimally support speech communication between teachers and the students as well as among students. For some classrooms, the criteria must be chosen to include meeting the needs of more sensitive groups of students. These would include, younger children and hearing impaired listeners, who need quieter conditions to understand speech well. This paper reports the results of new derivations of acoustical criteria from recently published classroom acoustics research studies and compares the new results with existing standards. The results of speech tests in classrooms were used to derive maximum acceptable values of ambient noise in classrooms for children of various ages. Similarly, optimum ranges of reverberation times were determined to maximize signal-to-noise ratios without excessive reverberation.

1. INTRODUCTION

Room acoustics criteria should ensure that the room fully supports the most important and most acoustically sensitive activities conducted in the room. In a classroom this is speech communication between teacher and students and between students. Most teaching activities are based on oral communication and this is particularly true for younger students. As many studies have shown[1,2], the accuracy of oral communication is easily degraded by even modest amounts of noise and unsatisfactory room acoustics. There is much evidence to show that these problems are more acute for younger children[2,3].

The accuracy of speech communication in a classroom is determined by two types of issues. The most important is the need to obtain conditions where the speech is of substantially higher sound level than interfering noise and other unwanted sounds. This requirement corresponds to having an adequate signal-to-noise ratio (SNR) at the listener and hence leads to a need to specify maximum acceptable ambient noise levels. The second area where criteria are required is to ensure that classrooms have optimum room acoustics. Optimum room acoustics is achieved by the appropriate control of reflected sounds in classrooms, which is typically expressed in terms of required reverberation times. While room acoustics and ambient noise levels are both important, most studies have shown excessive noise levels are much the larger problem. It is almost impossible for room reverberation to be as big a problem as excessive noise levels frequently are.

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This paper uses the results of recently published studies of conditions in classrooms and of children's ability to understand speech in noise[3,4] as well as in varied room acoustics[5]. These results were used to determine estimates of required maximum ambient noise levels and room acoustics criteria for young school children. The next section examines the requirements for maximum acceptable noise levels and the following section considers optimum room acoustics conditions for young children. This is followed by a discussion of how various related issues might influence the choice of classrooms acoustics criteria.

2. MAXIMM ACCEPTABLE AMBIENT NOISE LEVELS

We can determine acceptable maximum ambient noise levels for accurate speech communication from estimates of ideal signal-to-noise ratios and the speech levels found in classrooms.

A. Required Signal-to-Noise Ratios

To determine criteria for maximum acceptable ambient noise levels, we must have a good understanding of children's ability to understand speech in noise, as a function of age, and in conditions representative of typical classrooms. Such data is available from a recently published study of grade 1, 3 and 6 students (6, 8 and 11 year olds) in 41 different classrooms[3,4]. The Word Identification by Picture Identification (WIPI) test was used for children seated in their normal seats in their own classrooms. Fig. 1 shows one of the key results of this study describing how intelligibility scores increase with increasing SNR and the variations in the trends with the ages of the children. For very high SNR, at the right hand side of the figure, all age groups could get 98% or higher intelligibility scores, indicating that the children were familiar with the test words and could get near perfect scores for such ideal conditions. It is only when SNR values were lower than these very ideal values that intelligibility scores were reduced.

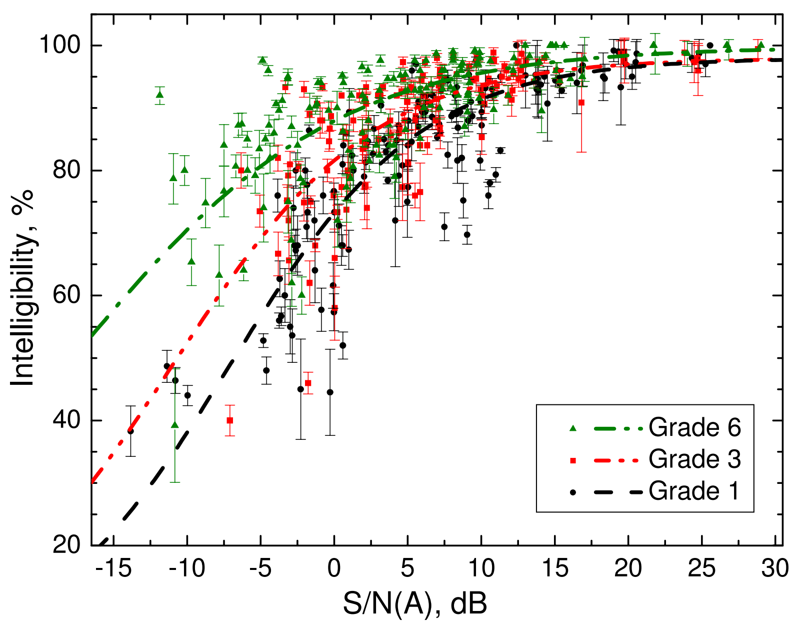

Fig. 1. Mean intelligibility scores of groups of approximately 5 students versus A-weighted signal to noise ratio (S/N(A)). The error bars indicate the standard deviations of the scores of each group of students. (from Fig. 2 reference 3).

Fig. 1 describes the ability of children of these 3 age groups to understand speech in noise. Of course, children with recognized hearing impairment and those using a second language would be expected to require quieter conditions for similar speech intelligibility scores.

There is considerable scatter about the regression lines in Fig. 1 and many student's scores deviated considerably from the mean trends. The study[3] analyzed this scatter and determined the fractions of each group of students that had very good scores defined as ≥95%. Fig. 2 plots the fraction of the students with speech intelligibility scores ≥95% versus S/N(A) for each of the 3 age groups.

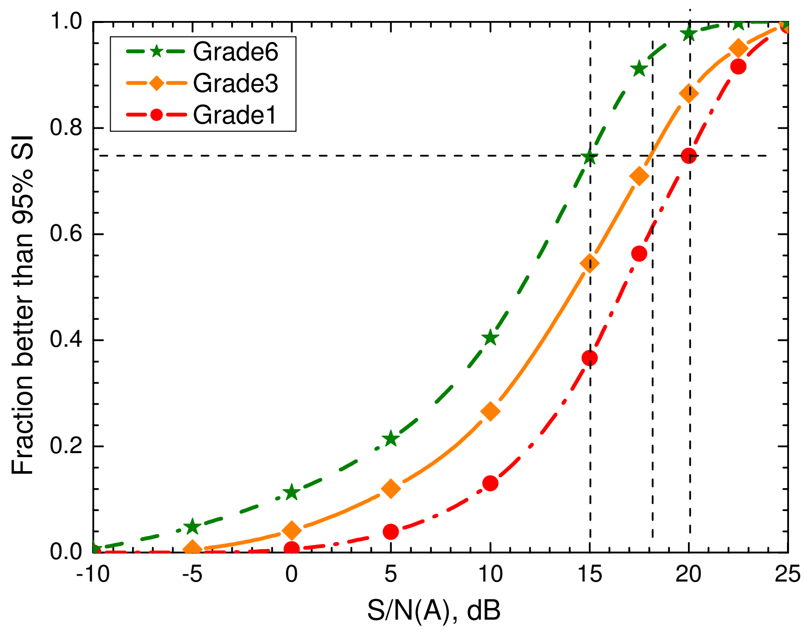

Fig. 2 Fraction of students with speech intelligibility (SI) scores ≥95% versus A-weighted signal-to-noise ratio (S/N(A)). (from Fig. 9 reference 3),

The horizontal dashed line in Fig. 2 indicates where 75% of the students would have intelligibility scores of ≥95% to aid in comparing the 3 age groups. Fig. 2 shows an S/N(A) of +20 dB is required for 75% of grade 1 students to get intelligibility scores of ≥95%. For 75% of the grade 3 students this S/N(A) is reduced to +18 dB and for the grade 6 students to +15 dBA. An S/N(A) of +15 dB[1,6] is often said to represent very good conditions for adults. Although slightly higher or lower criteria could be used (than 75% of students understanding at least 95%), this graph makes it possible to set criteria for required S/N(A) values for varied student age that are based on speech tests in realistic conditions in classrooms.

B. Speech Levels in Classrooms

The previous study[4] also recorded the sounds of teaching activities, during which the teacher was mostly talking, at 4 locations among the students in each classroom. By statistical analysis of these recordings, it was possible to determine mean speech levels from the distributions of speech and noise levels. Using the data from 27 conventional rectangular classrooms from the study, the mean speech level at the students due to their teacher talking to them was 60.1 dBA and the standard deviation of the speech levels was

4.3 dBA (Fig. 11, reference 1). This speech level is in the middle of the range of previously reported speech levels in classrooms[7].

The average speech levels would be influenced by the teacher-to-microphone distance and the acoustical properties of the classrooms. The teacher-to-microphone distances were not known. However, they are expected to be similar to the loudspeaker-to-microphone distances in the speech tests in the same rooms because the loudspeaker was placed where the teacher was typically located. The average loudspeaker-to-microphone distance was 2.3 m with a standard deviation of ±1.3 m. The classrooms were not very large (average room volume 198 m^3) and students were not far from the teacher. An average mid-frequency reverberation time of 0.41 s was reported[4] for occupied conditions in these classrooms.

C. Estimating Maximum Acceptable Noise Levels

Maximum acceptable ambient noise levels were calculated from the average measured speech level and the required S/N(A) determined from Fig. 2 for each age group. The calculations are summarised in Table 1. They simply subtracted one standard deviation of the speech levels and the required signal-to-noise ratio from the average measured speech levels to obtain the maximum acceptable ambient noise levels for very good speech communication. Using the mean speech level would lead to results that would provide ideal conditions for only 50% of the students. By basing the calculations on a speech level one standard deviation less than the mean, the results should apply to a wider range of classrooms and talkers.

	Grade 1	Grade 3	Grade 6
Speech level, dBA	60.1	60.1	60.1
Standard deviation	-4.3	-4.3	-4.3
Required S/N(A)	-20	-18	-15
Max. ambient noise	35.8	37.8	40.8

Table 1. Calculation of required maximum acceptable ambient noise levels to ensure conditions that would permit very good speech communication for each age group.

Several classroom acoustics standards[8,9] require a maximum ambient noise level of 35 dBA. The new estimates of the required maximum ambient noise levels confirm the suitability of these standard requirements for elementary school classrooms.

The calculations are intended to provide 75% of the students with conditions in which they will understand at least 95% of simple words, which are familiar to them. This would not be achieved at locations in the classrooms where the speech levels are more than one standard deviation below the measured mean value. Assuming a normal distribution of speech levels, one can estimate that in about 16% of the classrooms this goal might not be achieved. Such inferior conditions could correspond to teachers with weaker voice levels or to larger teacher-to-student distances.

From the results in Fig. 2 we can determine that a maximum ambient level of 35 dBA would increase the number of grade 1 students achieving 95% speech intelligibility or better to 80%.

3. OPTIMUM ROOM ACOUSTICS CONDITIONS

A. Optimising Room Acoustics for Speech Communication

The effect of room acoustics on the intelligibility of speech is often described in terms of the reverberation time of the room. However, the intelligibility of speech is not simply related to the room reverberation time and room acoustics can be more easily understood in terms of the reflected speech sounds that listeners hear in rooms. Early-arriving reflections, arriving within about 50 ms after the direct, sound can usefully enhance the effective SNR and the intelligibility of speech. In real rooms they have been shown to increase SNR values by 6 to 8 dB[10]. On the other hand, increased energy in later-arriving reflections of speech sounds, can decrease the intelligibility of speech. The optimum amount of sound absorption in a room and the related optimum reverberation time must correspond to a balance that provides as much early reflection energy as possible without too much later-arriving reflection energy. Simply striving for the lowest possible reverberation time will also lead to reduced SNR values and hence can create lower speech intelligibility. More difficult problems would then be created when teachers rove the classroom as they talk to students located in all directions around the teacher.

Experiments that simply vary the reverberation time of speech without including the related changes in speech level ignore the possible beneficial effects of added early arriving reflections of the speech sounds[11]. Of course, if the early reflections also increase the level of the interfering noises, there would be no net benefit. Hodgson and Nosal[12] argued, using calculations based on simple diffuse field theory, that the critical factor is the relative distance of the speech and noise sources from the listener. When the noise source is closer to the listener than is the speech source, they concluded that added early reflections would be beneficial and would increase SNR and speech intelligibility. In most classrooms the predominant source of noise is from the students who would typically be closer to the listener than would the talker.

B. Determining Room Acoustics Criteria

A recent investigation[5] evaluated the effects of reverberation time on speech intelligibility for children in grades 1, 3 and 6. They listened to speech with varied reverberation time for two different cases. In one case the speech levels were allowed to increase with the addition of increased reflected sound and in the other case the speech and noise levels were not influenced by the added reflected sound. They also included conditions that showed that children of all 3 age groups did benefit from the addition of early arriving reflections of speech sounds similar to adults.

Fig. 3 plots the trends of the mean speech intelligibility scores versus reverberation time (T_{60}) for the experiment in which the added reflections increased the speech levels and related SNR values. For each age group intelligibility scores were maximum between 0.6 and 0.7 s reverberation time. Although intelligibility scores were reduced for lower and higher reverberation times, the changes over the range from 0.3 to 1.2 s reverberation times were quite small. The larger differences between the different age groups are not due to reverberation but reflect the larger effect of SNR on the different age groups. (This data also included adult subjects who had a little better speech intelligibility scores than the grade 6 students).

Fig. 4 plots mean intelligibility scores versus reverberation time for a second experiment in which possible beneficial effects of added reflected sound were eliminated by fixing the SNR over the cases of varied reverberation times. When the beneficial effect of added reflected sounds were removed, intelligibility scores increased with decreasing reverberation time. Again there were large differences between age groups due to their varied sensitivity to SNR.

To determine optimum room acoustics conditions, it can be argued that the results in Fig. 3 are generally more relevant. In most classrooms the predominant sources of interfering sound are the other children who are usually closer to the listener than is the talker. This would lead to the conclusion that the preferred reverberation time for very good speech communication would correspond to a range of reverberation times from about 0.4 to 0.9 s. Speech intelligibility scores in Fig. 3 only vary by about 1% over this range.

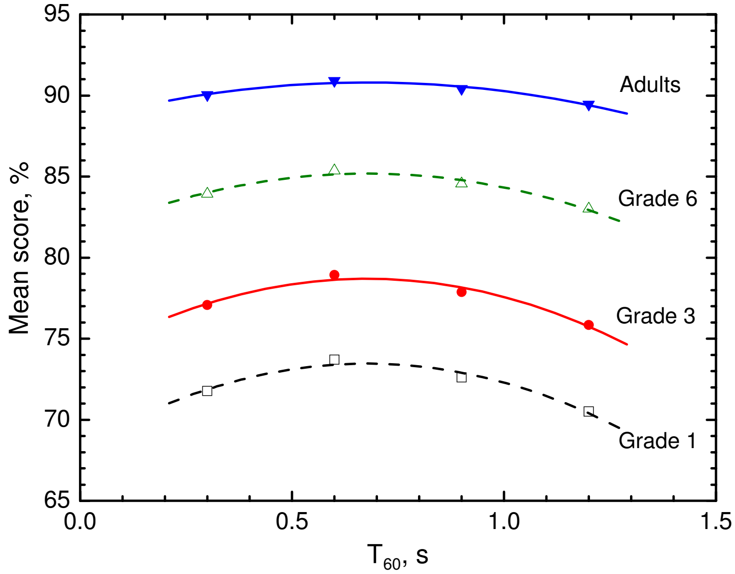

Fig. 3. Mean trends of intelligibility scores versus reverberation time (T_{60}) by age group for conditions with varied SNR. (Fig 12 from reference 5).

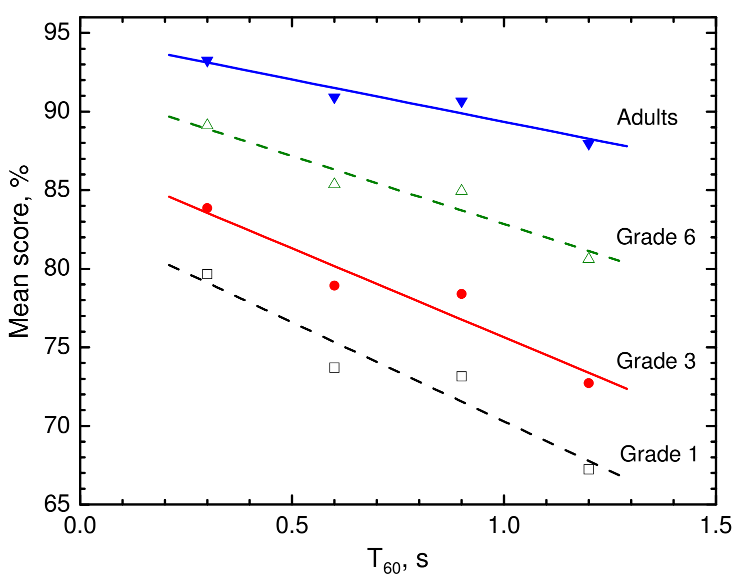

Fig. 4. Mean trends of intelligibility scores versus reverberation time (T_{60}) by age group for the case of constant SNR. (Fig 13 from reference 5).

There are other arguments that would further limit this preferred range of reverberation times. First, not all interfering noise is produced by nearby students. A longer reverberation time would tend to exaggerate the negative effects of such more distant noise sources and hence argue against a longer than necessary reverberation time. On the other hand, there are common situations in classrooms where strong early-arriving speech reflections are more important than indicated in these experimental results. In particular there are many situations where a teacher is not facing all students and strong early reflections are essential for some students to hear well. A recent study[13] has demonstrated the importance of reflected sound by showing that greater vocal effort is required in rooms lacking adequate reflected sound. These points argue against very short reverberation times. The combination of these arguments suggests that the ideal solution is to recommend a more limited range of reverberation times from about 0.5 to 0.7 s as optimum and from about 0.4 to 0.8 s as generally acceptable for occupied conditions.

4. DISCUSSION

This section discusses several issues that may influence the choice of criteria for achieving conditions for high quality speech communication in classrooms.

A. Why Focus Criteria on Speech Intelligibility Requirements?

This is simply because, speech communication is the most noise sensitive activity in classrooms and most educational activities are critically dependent on good speech communication. It is, of course, important that we base our criteria on the listening abilities of children of various ages in conditions representative of typical school classrooms.

B. The 35 dBA Criterion is Less than the Noise Made by the Students

If children produce higher noise levels than 35 dBA why do we need a criterion as low as 35 dBA? Children are typically the predominant source of disturbing sounds and ambient noise levels in occupied classrooms are almost always higher than in unoccupied classrooms[4]. However, much of the sounds from students are whispering and other low level chatting with other students. The level of this student noise increases with the level of other noise sources such as ventilation noise due to a Lombard type effect[14]. The Lombard effect describes the natural increases in speech levels by talkers attempting to be understood above competing noises. (New Zealand researchers refer to this increase in student noise levels as a *Café Effect*[15]). Because of this effect, the quieter the unoccupied conditions are, then the quieter will be the occupied conditions, and hence it is very important to reduce unoccupied ambient noise levels to very low levels.

C. Teaching Styles are Different Now

Various newer styles of teaching are claimed to be the new norm and it is suggested that they need different acoustical criteria. Teaching styles will continue to change and evolve. In the 41 classrooms we were in for our tests, teachers used a mixture of teaching styles. Even when students work in independent groups, there is often the need for the teacher to orally pass on information to all students in the classroom. It seems unlikely that teaching will evolve into some style that does not critically depend on oral communication among students and between teacher and students. Classrooms cannot be easily changed to meet specific needs of each new teaching style and should be designed to accommodate a variety of different types of uses. This again argues for criteria to support the most acoustically sensitive activities.

In the data from the recent classroom studies[3,4], that were used to determine the suitability of the 35 dBA criterion, the average talker-to-listener distance was estimated to be 2.3 m with a standard deviation ±1.2 m. This is not so different than the distance between some students working in groups. The current results are therefore thought to be suitable criteria for a range of teaching styles and classroom uses.

D. Student Voice Levels

The criterion for maximum acceptable noise levels was based on average measured speech levels of teachers. Often students have to talk so that their entire class can clearly hear their remarks. Our informal observation while in the classrooms was that their voice levels were often lower than those of the teacher and hence more difficult to understand. This does not agree with Pearsons data[16] that found for children between 6 and 12 years old the average 'normal' voice level was the same as for adult males but with a larger standard deviation. Classrooms should also fully support student talkers of all ages. To determine appropriate maximum ambient noise level criteria as a function of the talker's age may require more data on typical speech levels as a function of the age of the talker.

E. New Classroom Acoustics Research is Needed

The proposed criteria are thought to be suitable for a wide range of teaching styles and are based on a good understanding of children's ability to understand speech in conditions representative of classrooms. However, we do not fully understand the dynamics of how occupied classroom noise levels are influenced by the acoustical properties of classrooms. It may not be just a simple matter of adding absorption to reduce sound levels. It is possible that children's behaviour is influenced by the acoustical properties of the classroom, and that more or less benefit can be gained by absorptive treatments than we might predict from calculations of the sound level reductions due to added sound absorbing material. Such effects could be evaluated by detailed assessments in longitudinal studies of classroom renovations including measured levels of speech and noise during teaching activities.

5. CONCLUSIONS

Analyses to determine acoustical criteria for classrooms have been based on the results of recent speech intelligibility studies in classroom conditions. The data include a good understanding of children's ability, to understand speech in noise, as a function of age, in classroom conditions. The new data also describe the effects of room reverberation on the intelligibility of speech for young children in conditions representative of classrooms.

The analyses confirm that 35 dBA is a good criterion for an ideal maximum acceptable ambient noise level in unoccupied classrooms. This is the same as required in the US ANSI S12.60[8] and the UK BB93[9] documents. The results are appropriate for elementary school children and suggest that some high school aged students could cope well in slightly noisier conditions.

The criterion for optimum room reverberation time was concluded to be in the range from 0.5 to 0.7 s reverberation time for occupied conditions. Although values from 0.4 to 0.8 s would be equally acceptable for many situations, a discussion of other possible factors of influence concluded that lower and higher reverberation times should be avoided. Both ANSIS12.60 and BB93 recommend that reverberation times should not exceed 0.6 s for unoccupied conditions. The new results suggest these standards both have criteria that are a little too restrictive and also that they should also include minimum acceptable values.

The new results do not provide strong arguments for major changes to existing criteria for acoustical conditions in classrooms for elementary school aged children. They do confirm the importance of more careful control of ambient noise levels for younger children and that noise is almost always a bigger problem than poor room acoustics. New and renovated schools should meet the criteria in these standards.

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