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Effects of Room Acoustics on the Intelligibility of Speech in Classrooms for Young Children

W. Yang and J.S. Bradley

National Research Council, Montreal Rd., Ottawa, Canada, K1A 0R6

Email: John.Bradley@nrc-cnrc.gc.ca

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ABSTRACT

This paper reports new measurements of the intelligibility of speech in conditions representative of elementary school classrooms. The speech test material was binaurally recorded in simulated classroom conditions and played back to subjects over headphones. Subjects included grade 1, 3, and 6 students (6, 8 and 11 year olds) as well as adults. Recognizing that reverberation time is not a complete descriptor of room acoustics conditions, simulated conditions included realistic early-to-late arriving sound ratios as well as varied reverberation time. For conditions of constant signal-to-noise ratio, intelligibility scores increased with decreasing reverberation time. However, for conditions including realistic increases in speech level with varied reverberation time for constant noise level, intelligibility scores were near maximum for a range of reverberation times. Young children's intelligibility scores benefited from added early reflections of speech sounds similar to adult listeners. The effect of varied reverberation time on the intelligibility of speech for young children was much less than the effect of varied signal-to-noise ratio. The results can be used to help to determine ideal conditions for speech communication in classrooms for younger listeners.

I. INTRODUCTION

Most classroom learning involves oral communication and the intelligibility of spoken words is obviously very important for a successful learning environment. The intelligibility of speech in classrooms is influenced most by the speech-to-noise ratio (S/N) at the listener's position but also by reflected sounds and the age of the listener. All three factors must be considered when determining optimum conditions for speech communication in classrooms.

The effects of S/N and the age of the listener were recently investigated in classrooms of grade 1, 3 and 6 students (6, 8 and 11 year olds) [1,2]. In this previous work, speech intelligibility tests were performed by children listening naturally (binaurally) in their own classrooms with the natural ambient noises. The results gave a clear indication of the effects of both S/N and listener age on the resulting speech intelligibility scores and can contribute to determining optimum acoustical conditions for younger children.

Although the study tried to also examine the effects of varied room reverberation times, this was not successful because the 41 classrooms tested had similar and quite acceptable reverberation times. As a result, the current work was planned to consider the effect of varied room acoustics on the intelligibility of speech for children in school classrooms.

A number of previous studies have considered issues related to the effect of room reverberation on the intelligibility of speech in classrooms. However, the results of the various studies have some serious limitations.

Nábělek and Pickett [3] used a modified rhyme test with the speech and noise played back from two separate loudspeakers to investigate the effects of reverberation in classrooms. The test room had adjustable absorption making it possible to obtain conditions of 0.3 s and 0.6 s reverberation time. Although increasing the reverberation time also increased the sound levels by about 2 dB (page 630 of [3]), this effect was removed by adjusting the amplifier gains to create conditions with constant S/N. For the constant S/N conditions, the intelligibility scores increased for decreased reverberation time. However, if the natural increase in speech levels of 2 dB had been maintained for the 0.6 s reverberation time case, different results would have occurred with a reduced effect of varied reverberation time. The subjects were located approximately one critical distance from the loudspeakers and hence would have experienced approximately equal amounts of direct and reflected sound for an omni-directional source. Because the loudspeakers used would be more directional than a human talker, subjects may have actually experienced predominantly direct sound. The study can be criticized as providing conditions that would not accurately reflect the effects of reverberation on natural speech in many classrooms. They did not consider cases where the possible benefits of reflected sounds were present and they did not include younger listeners.

Nábělek and Pickett also demonstrated the binaural advantage of listening with two ears compared to monaural listening. Their results clearly demonstrate that the results of monaural listening tests (e.g. Finitzo-Hieber and Tillman [4], Johnson [5]) are not representative of normal listening conditions in rooms.

Neuman and Hochberg [6] assessed the effects of reverberation on the intelligibility of speech for children aged 5, 7, 9, 11 and 13 years old as well as adults. They used a speech test consisting of nonsense syllables and reverberation times of 0, 0.4 and 0.6 s. All speech samples were presented at the same level and in ‘quiet’ conditions. They obtained increasing intelligibility scores with increasing age of the listeners and with decreasing reverberation time. They also demonstrated the advantage of binaural listening for the 0.6 s reverberation time case. This was similar to a constant S/N experiment except that the noise level was very low. It is not possible to estimate the combined effect of reverberation time and S/N from these results.

Although studies in actual classrooms would be expected to more realistically determine the combined effects of S/N and reverberation time, in previous efforts it was not possible to find test classrooms with a wide range of reverberation times, S/N, and ages of listeners. An earlier study by Bradley [7] determined the combined effects of A-weighted speech - noise level differences (S/N(A)) and reverberation times (T_{60}) for 12 to13 year olds in their classrooms using regression analyses of combinations of predictors. Although S/N(A) values were the major determinant of intelligibility scores, reverberation time had a significant effect such that decreased reverberation time related to increased intelligibility scores. In a more recent classroom study [2], there were effects that indicated small increases in intelligibility scores with decreased reverberation times but not for the youngest subjects, i.e. the grade 1 students. Both results indicated that for a given S/N, increased reverberation time led to decreased speech intelligibility scores.

Most previous studies of the effect of reverberation on speech intelligibility have been for constant S/N or 'quiet' conditions with a presumably high S/N. None have specifically considered the possible benefits of added early-arriving reflected sounds that could increase effective S/N values. It has been shown for adult listeners, that added early reflections arriving within about 50 ms after the direct sound have the same effect as increasing the level of the direct sound and hence the added early-arriving reflections can usefully increase the S/N by 7 dB or more [8]. However, it has at other times been argued that increased reflected sound would increase both speech and noise levels and would result in no change to S/N values. Hodgson and Nosal [9] have explained that what is critical is the relative distances of the speech and noise sources from the listener. Their calculations, based on simple diffuse field theory, showed that when the noise source is closer to the listener than the talker, then added early reflections would usefully increase S/N values and hence would be expected to improve speech intelligibility. Yang and Hodgson [10] carried out speech intelligibility tests by auralizing virtual sound fields to support the earlier work [9]. Although they were largely successful, they did not give the actual signal-to-noise ratios of their conditions and they made no attempt to confirm that their conditions would represent the balance between early- and late-arriving sounds that would commonly occur in real rooms.

As the predominant source of interfering sound in classrooms is usually the children, it seems that the most common situation in elementary school classrooms is the case where the noise source is closer than the talker to the listener. For this case we would expect increased levels of early-arriving reflections to increase intelligibility scores because they would be relatively more important for the more distant speech source. Of course there are also many particular situations where early-arriving reflections are critical to understanding speech, such as when the talker is not facing the listener, or is at a more distant position in the classroom from the talker where the level of early-arriving speech energy can be as much as 7 dB or more greater than the direct sound [8]. These issues are rarely considered in more general discussions of classroom acoustics requirements, but commonly occur in classrooms.

This new research was planned to address several questions related to better understanding the effects of room acoustics on the intelligibility of speech for children in classrooms. It was thought important to understand the combined effects of reverberation time and S/N, which might occur in school classrooms, on the intelligibility of speech. In the new tests children should be listening naturally with two ears so that they could benefit from any binaural advantage that the realistic sound fields provided.

The new tests described in this paper were carried out using binaural playback of speech test material recorded in simulated conditions representative of real classrooms. Although tests in actual classrooms with varied T_{60} might be better, it was not possible to find the necessary combinations of room acoustic conditions and children's ages. Considerable effort was made to ensure that the simulated conditions were realistic representations of conditions in typical classrooms. Two types of combinations of T_{60} and S/N were created. In one series of conditions, reverberation time was varied and S/N was held constant. In a second series of tests, S/N values increased with the energy of the added reflected sound as longer T_{60} values were created. In a third experiment, some further conditions were created to determine how listeners benefited from added early reflections of the speech sounds. Tests were carried out on grade 1, 3 and 6 students (6, 8 and 11 year olds) as well as adults.

II. EXPERIMENTALPROCEDURE

The experimental procedure was to carry out speech intelligibility tests on elementary school students using speech test material binaurally recorded in simulated conditions representative of those in real classrooms.

A. Requirements for Simulated Classroom Acoustics Conditions

The intelligibility of speech is related to the level of the speech relative to the level of concurrent interfering noises. However, not all speech sound increases the intelligibility of the speech. Increased levels of the direct speech and early reflections of the speech arriving within about 50 ms after the direct sound lead to increased intelligibility, but later-arriving reflections reduce the intelligibility of the speech [8]. In simulating room acoustics conditions it is not good enough to simply vary reverberation times. It is possible to create unrealistic conditions with too much or too little early reflection energy that will lead to results that are not representative of conditions in actual classrooms.

The relative level of early reflection energy can be measured by C_{50} values, where C_{50} is an early-to-late-arriving sound energy ratio with a 50 ms early time interval [11]. When simulating conditions with varied reverberation time (T_{60}), it is important that C_{50} values are also appropriate for the corresponding T_{60}. Figure 1 illustrates combinations of C_{50} and T_{60} obtained from measurements in both classrooms [2] and auditoria.

It was desired to create test conditions with T_{60} values of 0.3, 0.6, 0.9, and 1.2 s, which were thought to correspond to the full range of likely conditions in typical elementary school classrooms. A T_{60} of 0.6 s is often thought to be near optimum [7] and is referred to in the ANSI S12.60 classroom acoustics standard [12]. A T_{60} of 0.3 s is representative of the lowest T_{60} values likely to be found in a normal classroom. T_{60} values of 0.9 and

1.2 s could occur in real classrooms but were expected to lead to increasingly less suitable conditions with lower speech intelligibility scores. Figure 1 also shows the combinations of measured C_{50} and T_{60} for the 4 simulated conditions. They are seen to be close to the mean trend of the results from the real rooms and hence corresponded to realistic ratios of early and late-arriving reflections.

One set of test conditions included these four T_{60} values and with a constant S/N. These would represent conditions in which the added reflected sounds equally influenced speech and noise levels. A second set of conditions was created in which speech levels increased as more reflected sound was added, while noise levels were held constant, leading to varied S/N. It was important to ensure that the increased speech levels with increasing T_{60} values realistically represented what would occur in real rooms.

The desired increase in speech levels with increasing T_{60} was determined from Beranek's compilation of measurement data. Figure 9.4 of reference [13] plotted values of $(EDT/V)\cdot 10^6$ versus G(mid) levels. (EDT is the early decay time, s, V is the room volume, m^3, G(mid) is the relative level or strength of the sound in the rooms and both EDT and G(mid) are for combined 500 and 1000 Hz octave band results). (See [11] for definitions of EDT and G). Beranek's plot relates the average variation in decay times to the average variation in levels for a large number of auditoria. These data were combined with data from several classroom-sized rooms and a new regression line fitted to the combined data, which was only very slightly different than Beranek's original line for large auditoria. The new line was used to predict the desired increases in level with varied decay time in the simulated conditions.

Beranek did not give the equation of his best-fit line but it was determined from his text and a manual fit of points from the line which indicates it is,

$$10\log\{(EDT/V)10^6\} = G_{mid} + 16 \quad (1)$$

Because we would like to predict G_{mid} values it is necessary to reverse x and y values as follows,

$$G_{mid} = 10\log\{(EDT/V)10^6\} - 16 \quad (2)$$

Fitting this form of equation to Beranek's large hall data combined with data for classroom sized rooms resulted in the following relationship,

$$G_{mid} = 10.75\log\{(EDT/V)10^6\} - 17.6 \quad (3)$$

Equation (3) was used to estimate increases in sound levels with increasing decay time for a 198 m^3 room volume which was the average room volume of the 41 elementary school classrooms recently studied [1]. The expected increases in level associated with the increased decay times using equation (3) are listed in Table 1 and plotted in Figure 2.

For comparison, the expected changes of level with decay time were also calculated using Barron's revised theory and diffuse field theory [14, 15] using a source-receiver distance of 5 m as representative of an average seat in a classroom. These calculated level changes were based on the measured T_{60} values of the simulated sound fields and the results are also included in Table 1 and Figure 2. The 3 approaches led to similar predicted increases in levels. Although the three sets of calculated level increases are all based on measured decay times, Beranek's relationship was based on EDT values while the others were based on measured T_{60} values. However the changes in levels were expected to be similarly related to EDT and T_{60} values. Measurements of the simulated sound fields demonstrated that the increases in speech levels varied in a similar manner as shown in Table 1 and Figure 2.

B. Subjects and Speech Test Procedures

The Word Intelligibility by Picture Identification (WIPI) speech test was used because it is a very simple test that 6 year olds and older students can quickly learn and respond to individually without significant training. It includes 4 lists of 25 phonetically balanced simple nouns [16, 17]. The test words were each presented in the carrier phrase, "Please mark the _____ now" spoken by a clear speaking female voice. These tests used exactly the same speech test recordings as in the previous classroom studies [1].

In the previous classroom study [1,2] students carried out the tests as groups while seated in their regular seat in their own classrooms and marked responses in a book of pictures illustrating the possible responses. In the current investigations, individual students were tested one at a time using headphone presentation of the speech material. The subject and experimenter were located in a quiet room without acoustical distractions and with no other people present. The processed speech test material was stored as wav files on a portable computer. These were presented to each listener using specially developed software that played the speech files and displayed the pictures corresponding to the possible 6 responses on a touch screen. The listener touched one of the 6 pictures to indicate the correct response. The program put an X through the touched picture to confirm which had been selected. The students found the test easy to perform and seemed to regard it as simple computer game.

All subjects first carried out a short practice test to be sure that they were familiar with the process of the test. If they had no problems they would then carry out the actual tests. The grade 1 students each carried out tests of 3 different conditions. The grade 3 and 6 students as well as the adults each carried out tests for 4 different conditions. The use of each of the 4 word lists was rotated so that all 4 word lists were used an approximately equal number of times to asses the 9 different acoustical conditions by each age group of subjects.

The students were from several schools in the Ottawa Carleton District School Board (OCDSB). Permission to invite schools and students to participate in our tests was obtained from the OCDSB Research Advisory Committee. Ethics approval was obtained from both the University of Ottawa Research Ethics Board (protocol H 03-07-06) and the National Research Council Research Ethics Board (protocol 2007-10). All students volunteered to participate with the written consent of their parents. Adult participants volunteered and each signed consent forms. A total of 77 grade one students, 75 grade three students and 65 grade six students participated. In addition 17 adults were tested.

C. Sound Field Simulation and Headphone Playback Procedure

Conditions simulating those in classrooms were created using an 8-channel electroacoustic sound field simulation system located in an anechoic room and quite similar to a previously described system [8]. The System consisted of 8 Tannoy model 800A loudspeakers that surrounded the listening position. Five of the loudspeakers were in the horizontal plane of the listener's ears and the other 3 were raised up above this plane in front of the listener.

The signals to each loudspeaker were processed by four Yamaha DME32 digital signal-processing units connected together to form one large unit. A direct speech sound arrived first from the loudspeaker directly in front of the listening position. A total of 31 early reflections were created that arrived from the 8 loudspeakers within 50 ms after the direct sound and realistically decreased in level with increasing time. Reverberant decays followed the discrete early reflections. Reverberation times were varied by varying the decay times of the digital reverberator components in the DME32 units. Adjusting the balance between the combination of direct sound and early reflections versus late-arriving sound made it possible to adjust C_{50} values independent of T_{60} values to create the desired combinations of C_{50} and T_{60} values in each octave band from 125 to 8k Hz. This setup made it possible to systematically vary the most relevant aspects of the sound fields and to ensure that realistic combinations were obtained.

To record speech test material for each test condition, an acoustical mannequin (Brüel and Kjaer type 4128) was placed at the listener position. For the younger (and smaller) listeners, a smaller head would have been desirable but such heads are not commercially available. The speech test material was played through the 8 loudspeakers of the simulation system and recorded using the microphones in the acoustical mannequin. It was subsequently played back to listeners over Sennheiser type HD280 headphones. In recording the speech in this way, the frequency response of the speech was modified by the frequency response of the acoustical mannequin. When playing the recordings back to subjects, the frequency response of the speech was further modified by the characteristics of the headphones. The frequency response of the test speech material was corrected by measuring the combined response of the headphones and acoustical mannequin. The transfer function of the combined headphones and acoustical mannequin was obtained by measuring the impulse response of the headphones while placed on the acoustical mannequin.

One of the major difficulties of using headphone playback is that re-positioning the headphones leads to different headphone transfer-functions and in some cases these differences can be quite large [18]. Initial tests confirmed that large variations in the measured transfer functions are possible and to minimize these effects, the head and headphone transfer function was determined from the average of 10 different placements of the headphones on the acoustical mannequin. For each repeat, the headphones were carefully positioned on the mannequin so that the headphone cushions completely covered the pinna of the acoustical mannequin. The average transfer-function was determined from the average measured impulse response after carefully aligning the start of each measured impulse response.

The recorded speech test material was equalized to correct for the head-headphone transfer function. This was done by deconvolution of the recorded speech with the average measured impulse response of the head-headphone combination to extract the effects of the head and headphones from the recorded speech. The process was evaluated by comparing the levels of speech initially recorded at the mannequin with the levels of the same speech played back from headphones after processing and again recorded at the microphones of the mannequin. The differences are plotted as 1/3-octave band levels in Figure 3 for conditions 1 to 4 having T_{60} values of 0.3, 0.6, 0.9 and 1.2 s (see next section and Table 4 for description of conditions). For frequencies from 250 Hz to 6.3k Hz inclusive the differences were 1 dB or less. However, the headphone playback always had slightly lower levels with an average difference over the 250 to 6.3k Hz range of 0.6 dB. This was thought to be due to using an average correction. There were larger differences at frequencies below 250 Hz and these differences increased with decreasing reverberation time of the test condition. These effects are not important for speech intelligibility [19] but are similar to previous observations that auralization of more absorptive conditions can be more difficult [20].

Simulated ambient noise was separately recorded binaurally in a similar manner. Noise with a -5 dB per octave spectrum shape was produced and radiated incoherently from all 8 loudspeakers in the sound field simulation system. This spectrum shape has been shown to approximate typical indoor ambient noise such as that from ventilation systems and is often referred to as a ‘neutral’ spectrum [21, 22]. The binaural noise recordings were corrected for the response of the headphones and mannequin as described for the speech sounds. The noise recordings were mixed with the speech recordings at levels to provide the desired signal-to-noise ratios.

D. Test Conditions

Speech tests were carried out for 9 different acoustical conditions making it possible to carry out 3 different experiments. Table 2 summarises the 9 test conditions.

Conditions 1 to 4 were used in experiment #1 in which reverberation time was varied (0.3, 0.6, 0.9 and 1.2 s) and the ambient noise level was held constant. As a result, S/N(A) increased with increasing reverberation time representing the expected increase in speech level due to the addition of reflected sounds with increasing T_{60}.

Conditions 7, 2, 8 and 9 were used in experiment #2. Again reverberation time was varied (0.3, 0.6, 0.9 and 1.2 s) but the S/N(A) was kept constant in this experiment. This experiment would represent the condition where added reflected sound leads to equal increases in both speech and noise levels.

Experiment #3 included conditions 5, 6 and 3. Condition 5 included direct speech sound only. In condition 6 early reflections were added which increased the total sound level. Finally, condition 3 had the same level of direct sound and early reflections, but with added late-arriving sound. The ambient noise level was held constant and hence the overall speech levels increased as reflected sounds were added. This experiment was intended to determine whether young children benefit from added early-arriving reflections in a manner similar to adults.

The number of subjects tested for each of the 9 conditions varied a little with the age of the subjects and slightly among the different conditions for each age group as summarised in Table 3.

E. Validation of Headphone Playback Procedure

Acoustical conditions A to D were used in initial tests to validate that the headphone playback process led to the same intelligibility scores as direct playback of speech sounds for the same acoustical conditions. Conditions A to D were the same as Conditions 1 to 4 except that some S/N(A) values were a little different. The comparison test used 16 adult subjects who each carried out the tests both by direct listening in the anechoic chamber simulation system (AC) and also by listening over headphones (HP). Figure 4 shows that the mean scores for each condition were very similar for the two types of playback of the speech and noise sounds.

The differences were tested using a paired-samples T-test. When all conditions were included as a group, there was not a significant difference between the two playback methods. When the pairs of results for each of the 4 acoustical conditions were separately tested, in all cases there were no significant differences between the two playback methods. That is, we can be reasonably confident that our processed recordings played back over headphones were equally intelligible to the speech in the original sound fields. This confirmed earlier exploratory studies to consider the viability of the headphone playback method [23].

Marshall [16] found that the 4 word lists of the WIPI test did not yield identical scores for evaluations of the same acoustical conditions. As all of the 4 word lists were used approximately equally for each acoustical condition, it was possible to compare the mean scores from each word list averaged over all acoustical conditions. This was done first for the adult listeners so that they could be used for the results of the initial validation tests of the playback procedure. Table 4 lists the mean adult scores for each of the 4 word lists of the WIPI test averaged over all acoustical conditions. This is followed by the corresponding corrections for the adult data, for the children's responses and for the combined adult's and children's responses ('both'). (Of course the corrections for children and 'both' adults and children were determined later but are included here for easy comparison). Marshall's corrections for children aged 5 to 11 years old are included in the final column and are seen to be reasonably similar to those for children from the current study.

The corrections indicate how the average response for each word list differed from the average of all word lists. The adult corrections shown in Table 4 for adult subjects were used to correct the scores from the validation test results by dividing each score by the appropriate correction value depending on the word list that was used. The resulting corrected scores are shown in Figure 5.

The corrections result in a little closer agreement between the two sets of data. However, the pairs of results were not significantly different before correcting for word list differences and were again not significantly different after correcting for the word list differences (paired-sample T-tests). The results do suggest that there is a small benefit to correcting scores for word list differences and the mean squared difference between headphone and direct acoustic playback was reduced from 2.02 to 1.57 when the scores were adjusted to correct for word list differences.

The differences among the word lists may be due to a number of factors. Most obvious would be the different test words that make up each list. Some lists may contain a few more difficult words than other lists. However, there may also be differences related to how well the talker spoke each test word and how well each test word was recorded. In addition the age of the listener may influence the corrections because younger listeners would be more affected by more difficult words. The corrections included in Table 4 were probably influenced by all of these factors and so we would not expect our new corrections to be the same as Marshall's.

III. RESULTS OF THE THREE MAIN EXPERIMENTS

The results of all three experiments described in the following sections were first analyzed in terms of the uncorrected speech intelligibility scores and subsequently using the corrected scores as described in the previous section using the 'both' correction values from Table 4. In all cases using the corrected scores did not change the pattern of results but led to small improvements in the significance of the results. Therefore, to avoid unnecessary confusion, the following results of the three main experiments are described only in terms of the corrected scores.

A. Experiment #1 (varied S/N)

In Experiment #1 subjects listened to speech for conditions 1 to 4 (described in Table 2). These were conditions of varied T_{60} for constant noise level resulting in varied S/N as might occur when added room reflections of speech sounds increase the effective S/N. An analysis of variance of the corrected speech intelligibility scores indicated significant main effects of Age ($p<0.001$) and Condition ($p<0.003$). There was not a significant interaction effect. A Tukey HSD posthoc test of the data indicated that the differences between each of the 4 age groups were all significant ($p<0.014$ or better).

The mean corrected scores are plotted versus condition for each age group in Figure 6. The error bars show the standard errors of each mean score. A fifth line on Figure 6 plots the average results over all age groups versus acoustic condition. Although there are not large variations in the scores with varied T_{60}, the average of all ages tends to peak for condition 3 with a T_{60} of 0.9 s. For these cases, where added reflected sound increased both S/N and T_{60}, there is a range of conditions that lead to approximately the same speech intelligibility scores within each age group.

B. Experiment #2 (fixed S/N)

Experiment #2 included conditions 7 2, 8 and 9 that had a constant S/N(A) of –2 dB for cases with T_{60} varying from 0.3 to 1.2 s, as described in Table 2. An analysis of variance of the corrected scores for all age groups and these 4 conditions indicated highly significant main effects of both Condition and Age ($p<0.001$). There was not a significant interaction effect. A Tukey HSD posthoc test of the data indicated that the differences between pairs of the 4 age groups were all significantly different ($p<0.001$ or better). The mean values and their standard errors for the corrected scores are plotted in Figure 7.

When the S/N was held constant, as in these results, there is no beneficial effect of increased reflected speech sound and there is a trend for speech intelligibility to decrease with increasing reverberation time.

C. Experiment #3 (added reflections)

Conditions 5, 6 and 3 were used in Experiment #3 to examine the basic effects of first adding early-arriving reflections to the direct sound, and second adding late-arriving reflections. By comparing the results from condition 6 with those of condition 5 we can determine the effects of adding early-arriving reflections to the direct speech sounds. An analysis of variance of the corrected results from conditions 5 and 6 showed that there were significant changes in the intelligibility scores with Condition ($p<0.001$) and Age ($p<0.001$) but no interaction effect. The lack of a significant interaction effect indicates that all ages of listener benefited equally when early-arriving reflections were added. A Tukey HSD posthoc test of these data indicated that the grade 6 and adult results were not significantly different but the results of all other age groups were different than each other ($p<0.011$ or better).

The mean corrected scores are plotted in Figure 8. Adding early reflections increased speech intelligibility for all age groups but the scores of the adults were not significantly different than those of the grade 6 students.

Comparing the scores from conditions 3 and 6 makes it possible to determine the effect of adding late-arriving speech sounds with a 0.9 s reverberation time. An analysis of variance of the corrected data from these two cases indicated a significant effect of Age ($p<0.001$) but no significant effect of Condition. A Tukey HSD posthoc test showed that the Age differences were not significant for all age groups. The results of the grade 1 and grade 3 students were not significantly different and the results of the grade 6 and adult listeners were not significantly different, but other differences among Age groups were significant. Adding late-arriving reflections did not significantly change speech intelligibility scores even though the overall speech level increased when the reverberant speech was added. The averages of all age groups shown in Figure 8, suggest a small decrease in intelligibility but this was not statistically significant (i.e. $p = 0.07$).

IV. DISCUSSION

A. Comparisons with Previous Results

It is of interest to compare the new results from the current study with previous results to confirm that they are representative of children's experience in real classrooms and that the effects of reverberation are similar to those in previous studies.

Previous speech intelligibility tests in classrooms [1,2] related speech intelligibility scores using the WIPI test to S/N(A) values. In the previous classroom study, the predominant source of interfering sound was concluded to be the children, because occupied noise levels were higher than unoccupied noise levels even when the children were inactive and quiet [2]. Therefore we can assume that the results of experiment #1 are most representative of the conditions in the classrooms. Figure 9 compares mean speech intelligibility scores from the current study with the speech intelligibility scores versus S/N(A) values for grade 1, 3 and 6 students from the previous classroom study.

For each age group in the current study, the results of conditions 1 and 2, corresponding to T_{60} values of 0.3 and 0.6 s, are plotted on Figure 9 at the appropriate S/N(A) values. The mean occupied classroom reverberation time was 0.41 s [2] and was intermediate to the two conditions plotted from the current data. For the grade 6 results there is near perfect agreement between the current results and the classroom study results. The grade 3 results from the current study indicate slightly higher mean intelligibility scores than the classroom study and the grade 1 results indicate a little larger difference. The two studies used exactly the same speech test material, the same age groups, and the acoustical conditions of the new study were intended to closely model those in classrooms. However, there are other differences that might have affected the youngest listeners. While the acoustical conditions may have been quite similar, in the actual classrooms there were many other forms of distraction that might have reduced the scores of the youngest listeners. These other distractions would include visual distractions such as those of the other children's actions. In addition, the interfering sounds in the classroom were not always meaningless broadband noise, but at times were recognizable sounds from both within their classroom and from adjacent spaces. These may have had a larger negative effect on speech intelligibility scores. Considering the differences in the two experimental procedures, the agreement is very good and confirms that classroom conditions were accurately simulated.

There is little previous data available that can be compared with the current results indicating the effects of varied reverberation time for young children in conditions representative of classrooms. Most previous studies have included major procedural differences such as monaural presentation of the speech, different speech test material, or quite different and often unrealistic acoustical conditions. In spite of some differences in experimental methods, the current results of Experiment #2 were compared with the results of Neuman and Hochberg [6] in Figure 10.

Neuman and Hochberg tested children aged 5, 7, 9, 11 and 13 years old as well as adults. They included 3 acoustical conditions corresponding to no reverberation, and reverberation times of 0.4 and 0.6 s. However, they did not specify the ambient noise level during the tests and only indicated it to be 'quiet'. In addition, their speech test material was different than the current study and consisted of nonsense syllables.

To obtain more comparable results, their scores for 5, 7 and 9 year olds were interpolated to get values representative of 6 and 8 year olds. Figure 10 indicates reasonable agreement in the general trends of the data with intelligibility scores increasing with decreasing reverberation time. The adult and 11 year old (grade 6) data for the two studies agree very well for comparable T_{60} values. The results of the 8 year olds (grade 3) indicate some differences and for the data of the 6 year olds (grade 1), the current study produced much lower speech intelligibility scores. This is probably largely due to different signal-to-noise ratios between the two tests, which would more adversely affect the youngest listeners[1]. In Experiment #2 the S/N(A) was -2 dB and was presumably much lower than for the Neuman and Hochberg results in 'quiet' conditions. In view of the significant differences in the procedures of the 2 studies, the agreement seems reasonably good and generally indicates the same effects of reverberation for cases of constant S/N.

The results of Experiment #3 cannot be directly compared with previous results because no previous study could be found that considered whether young children benefit from added early-arriving reflections of speech sounds. Although studies with adults have clearly demonstrated that the added energy of early-arriving reflections within about 50 ms of the direct sound increases speech intelligibility equivalent to a similar increase of the direct sound level [8], this has not been demonstrated for children. Some have argued that children do not benefit from early-arriving reflections [24]. The results of Experiment #3 confirm that children do benefit as much as adults do when early reflections are added. The non-significant effect of adding later arriving sound is also similar to previous results for adult listeners [8].

B. Determining Ideal Conditions for Speech Communication in Classrooms

In Experiment #1, speech intelligibility scores tended to peak at some intermediate T_{60} value as expected for the conditions with varied S/N, but there were not large variations in intelligibility scores over the included range of T_{60} values. Because the Experiment #1 results shown in Figures 6 were based on data from only 4 conditions, and a small range of T_{60} values, it is difficult to accurately determine the mean trends.

To obtain a better estimate of the mean trends, the speech intelligibility scores for all of the 9 conditions were plotted versus the corresponding Useful-to-Detrimental sound ratios (U_{50}) for each of the conditions. This made it possible to use 9 data points rather than 4 to determine the mean trends of the data. It is well known that U_{50} values can explain the combined effects of varied S/N and varied T_{60} on speech intelligibility scores [7, 9, 25, 26]. Useful-to-Detrimental sound ratios were calculated from measured C_{50} values along with measured speech and noise levels in the six octave bands from 125 to 4k Hz as described in [26]. The octave band U_{50} values were arithmetically added with a uniform frequency weighting. The mean scores from all 9 conditions are plotted versus U_{50} values for each age group in Figure 11. Because the range of conditions is not large, the variation of speech intelligibility scores with U_{50} values is approximated by linear regressions lines in Figure 11. Smoothed speech intelligibility scores that represent the average trend of the data can be determined from these linear regression lines. These smoothed scores should provide a more accurate indication of the mean trend of the data for each of the experiments.

The smoothed speech intelligibility scores for the Experiment #1 conditions from the regression lines in Figure 11 are plotted versus T_{60} values in Figure 12. These show what is believed to be better estimates of the mean trends of the Experiment #1 results. Figure 12 shows approximately parallel curves peaking at a T_{60} of 0.68 s. That is, for these conditions this T_{60} value provides the best speech intelligibility. However, speech intelligibility scores are not substantially lower for a wide range of reverberation times. From Figure 12 one could conclude that of the test conditions only the 1.2 s reverberation time condition showed a significant reduction in mean speech intelligibility score for the smoothed results of Experiment #1. When the curves on Figure 12 are examined more carefully, they are seen to vary in curvature and are not quite parallel. The curvature increases with decreasing age of the listeners, possibly suggesting that younger listeners are more sensitive to the negative effects of reverberation. However, these effects are too small to be practically important and were not statistically substantiated.

Smoothed values for the Experiment #2 results were also obtained from Figure 11 and are plotted versus T_{60} values in Figure 13. As expected this figure shows speech intelligibility scores increasing with decreasing T_{60}. However, it can now be seen that the rate of variation of speech intelligibility scores with T_{60} is greatest for the youngest listeners. That is, the negative effects of increasing reverberation time more rapidly degrade conditions for the youngest listeners.

V. CONCLUSIONS

The new results in this study provide statistically significant evidence of the effects of reverberation time and the age of the listeners on the intelligibility of speech in elementary school classrooms.

For the conditions of constant noise level and varied S/N in Experiment #1, speech intelligibility scores were near maximum (within 1%) for a wide range of reverberation times. The new results indicate that for these varied S/N conditions, acceptable reverberation times can be described as the range from about 0.3 to 0.9 s reverberation time. The varied S/N conditions of Experiment #1 are thought to be most representative of conditions in elementary school classrooms where the dominant sources of interfering sounds are the nearby children.

These results suggest that the natural increase in speech levels with the increased early reflection energy associated with increased reverberation time compensate for the negative effects of the concurrent increase of late-arriving speech sound with increasing reverberation time. However, if the constant noise level used in Experiment #1 were increased or decreased the range of acceptable reverberation times would change. Previous studies have demonstrated that preferred reverberation times for speech increase with increased noise levels [27].

For conditions of constant S/N (Experiment #2), speech intelligibility scores increased with decreasing reverberation times and the effect was most rapid for the youngest listeners. However even for high S/N conditions, having some reflected sound can be critical to understanding speech and hence very low reverberation times should not be recommended. For example, when the talker's head is turned or when listeners are more distant from the talker, adequate speech intelligibility depends on reflected sound and in such cases early-arriving reflections can increase S/N by 7 dB or more [8].

The addition of early-arriving reflections of speech sounds was confirmed to be equally beneficial for young children and for adults.

While the younger children always had lower speech intelligibility scores, this was mostly due to younger children being more adversely affected by interfering noise [1]. However, there were small indications that younger children were more adversely affected by reverberation. For the varied S/N conditions (Experiment #1), the range of acceptable reverberation times decreased very slightly with decreasing age of the listener. For the constant S/N conditions (Experiment #2), the decrease of intelligibility scores with increasing reverberation time was a little more rapid for younger listeners. However, the magnitude of the negative effects of reverberation on speech intelligibility were much smaller than previously found for varied S/N and the effects of reverberation varied much less with the age of the listener.

An ideal approach to the acoustical design of classrooms would be to first reduce all noise levels (at the source if possible) and then design the reverberation time of the room to optimise the provision of added reflected sound to enhance speech levels. The current results suggest that design criteria should not specify maximum reverberation times. They should specify a range of acceptable values. Too little reflected sound is a potentially expensive and serious problem.

This study has considered how the physical characteristics of the classrooms affect the intelligibility of speech. The situation in real classrooms is more complicated than in the current tests because often the major factor influencing intelligibility is the interfering sounds made by the children. The levels of sound from the children and their behaviour may also be affected by the acoustical treatment of the classroom. Further studies are needed to compare conditions in treated and untreated classrooms to help understand the interactions of the behaviour of students and teachers with the acoustical treatment of classrooms.

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T_{60}, s	Increase in G(500,1000), dB			
	Beranek	**Barron**	**Diffuse**	**Measured**
0.3	0.0	0.0	0.0	0.0
0.6	3.2	3.7	2.8	2.8
0.9	5.1	5.8	4.5	5.5
1.2	6.5	7.2	5.8	7.3

Table 1. Expected increases in sound levels with increasing decay time relative to the case of a T_{60} value of 0.3 s as well as the level increases measured in the simulated sound fields.

Condition	T_{60}, s	Speech level, dBA	Noise Level, dBA	S/N(A)
1	0.3	62	67	-5
2	0.6	65	67	-2
3	0.9	67	67	0
4	1.2	69	67	2
5	Direct only	60	67	-7
6	Direct+early	66	67	-1
7	0.3	62	64	-2
8	0.9	67	69	-2
9	1.2	69	71	-2

Table 2. Description of the 9 acoustical conditions used in the speech tests.

Age	N
Grade 1	24 – 26
Grade 3	29 - 36
Grade 6	26 – 31
Adults	14 –16

Table 3. Numbers of subjects (N) that participated in each test condition for each age group.

Word list	Mean score	Correction adults	Correction children	Correction both	Correction Marshall
1	93.78	1.0509	1.0621	1.0565	1.0115
2	90.59	1.0153	1.0249	1.0201	0.9606
3	82.63	0.9259	0.9112	0.9186	0.9022
4	89.94	1.0079	1.0018	1.0048	1.1257
Average	**89.233**	**1.0000**	**1.0621**	**1.0565**	**1.0115**

Table 4. Mean scores for each word list and correction factors of the WIPI test for adult listeners, followed by corrections for adults, children, both (adults and children) and Marshall's corrections from Table 22 of [16].

Figure Titles

Figure 1. Measured octave band values of C_{50} plotted versus the corresponding T_{60} values. Open triangles: classroom data, open squares: measured auditorium data, closed circles: simulated sound fields, solid line: best fit regression line.

Figure 2. Variation of sound levels with decay time plotted as mid-frequency G values versus measured mid-frequency EDT values corresponding to the conditions with T_{60} values of 0.3, 0.6, 0.9 and 1.2 s for 198 m^3 room. Solid circles: simulated conditions, open triangles: classroom sized room data, solid line: equation (3). (color online)

Figure 3. Level differences between 1/3 octave band speech levels of the initial acoustical mannequin recordings (AC) and recordings of the processed initial recordings played back over headphones (HP). The differences for the left (L) and right (R) ear recording for conditions 1 to 4 having T_{60} values of 0.3 to 1.2 s are shown. (color online)

Figure 4. Comparison of mean speech intelligibility scores for headphone playback (HP) and direct playback in the anechoic chamber simulation system (AC). Error bars indicate the standard errors of each of the mean values. (color online)

Figure 5. Comparison of corrected mean speech intelligibility scores for headphone playback (HP) and direct playback in the anechoic room simulation system (AC). Error bars indicate the standard errors of each of the mean values. (color online)

Figure 6. Mean corrected scores for conditions 1 to 4 having T_{60} values 0.3, 0.6, 0.9 and 1.2 s respectively. Each line refers to the data from a different age group and the error bars are the standard errors of each mean value. A fifth line indicates the averages of all 4 age groups. (color online)

Figure 7. Mean Corrected scores for conditions 7, 2, 8 and 9 having T_{60} values 0.3, 0.6, 0.9 and 1.2 s respectively and a constant S/N(A) = -2 dB. Each line refers to the data from a different age group and the error bars are the standard errors of each mean value. A fifth line indicates the averages of all 4 age groups. (color online)

Figure 8. Mean corrected scores for condition 5 (direct sound only), condition 6 (direct sound and early-arriving reflections) and condition 3 (direct sound with early and late-arriving reflections). Each line refers to the data from a different age group and the error bars are the standard errors of the mean values. A fifth line indicates the averages of all 4 age groups. (color online)

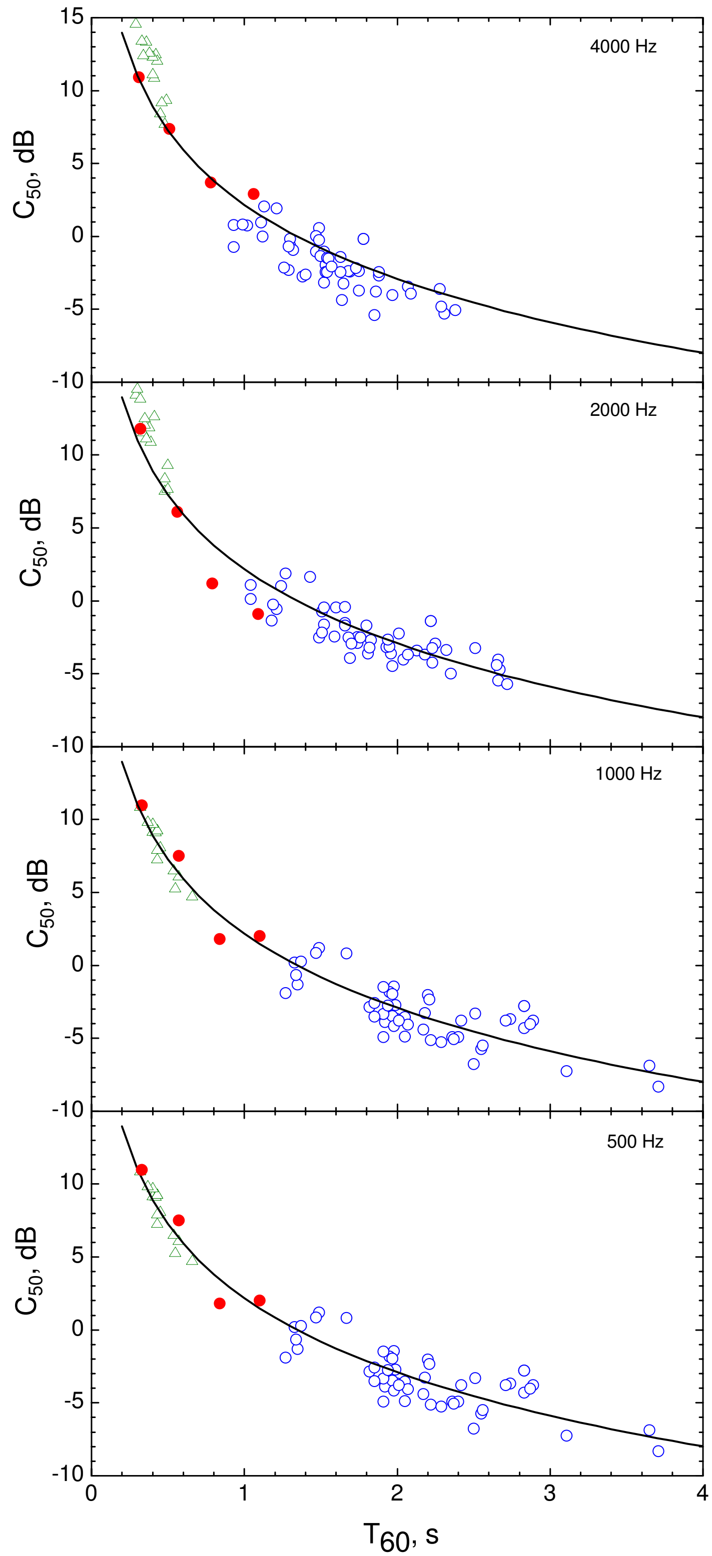
Figure 9. Comparison of mean speech intelligibility scores from conditions 1 and 2 (T_{60} 0.3 and 0.6 s) with previous classroom study results. Large filled symbols are the new results; small open symbols and regression lines are from the previous classroom study (Figure 2 of reference [1]). (color online)

Figure 10. Comparison of experiment #2 results with those of Neuman and Hochberg [6]. The 6 and 8 year old data were from interpolations of Neuman and Hochberg's data for 5, 7 and 9 year olds. (color online)

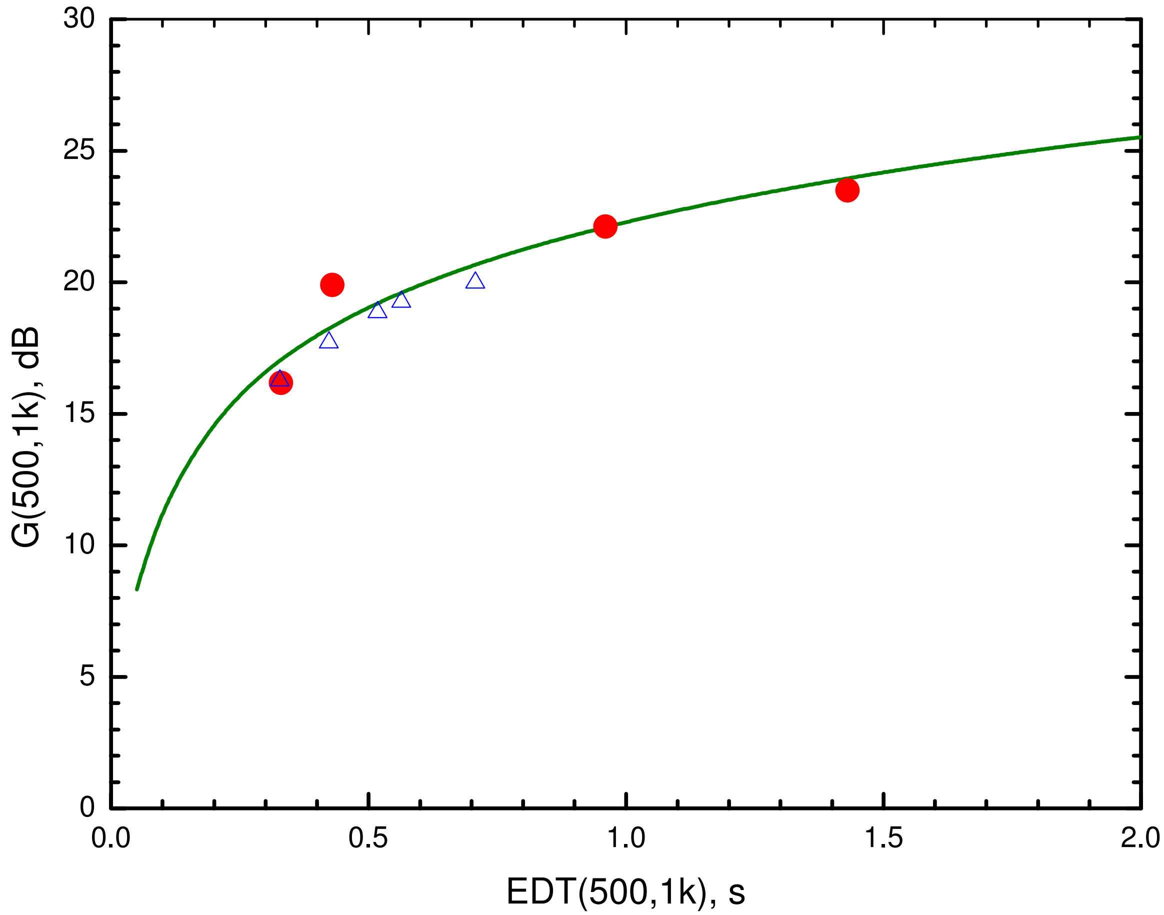
Figure 11. Plot of mean speech intelligibility scores versus U_{50} values for each of the 9 conditions and for each age group with associated linear regression lines for each age group. Each vertical dotted line indicates the data for one condition as labelled at the top of the graph. (color online)

Figure 12. Smoothed speech intelligibility scores plotted versus T_{60} values for the results of Experiment #1 with conditions having varied S/N values. The curved lines are second order polynomial regression lines to the data. (color online)

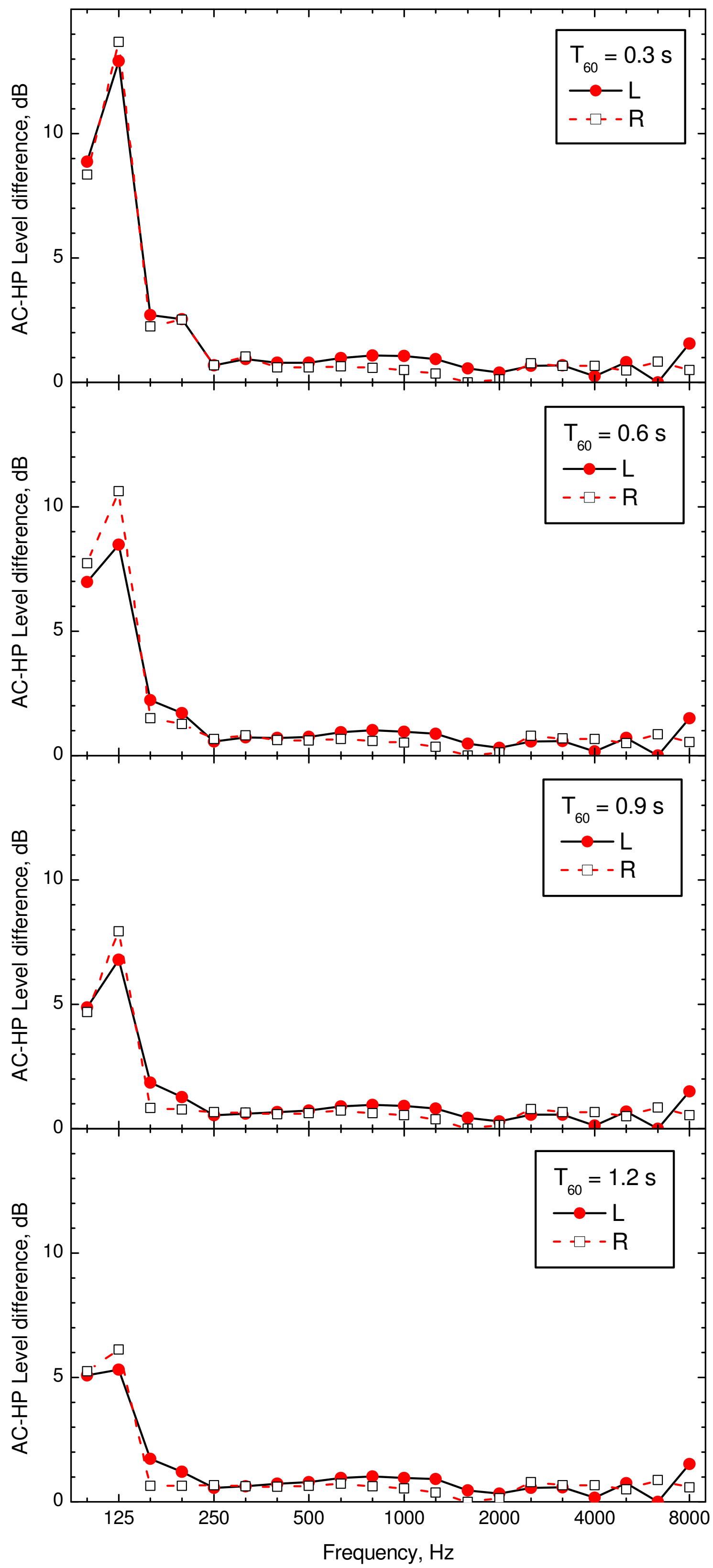
Figure 13. Smoothed speech intelligibility scores plotted versus T_{60} values for the results of Experiment #2 with conditions having constant S/N value. The lines are linear regression lines to the data for each age group. (color online)



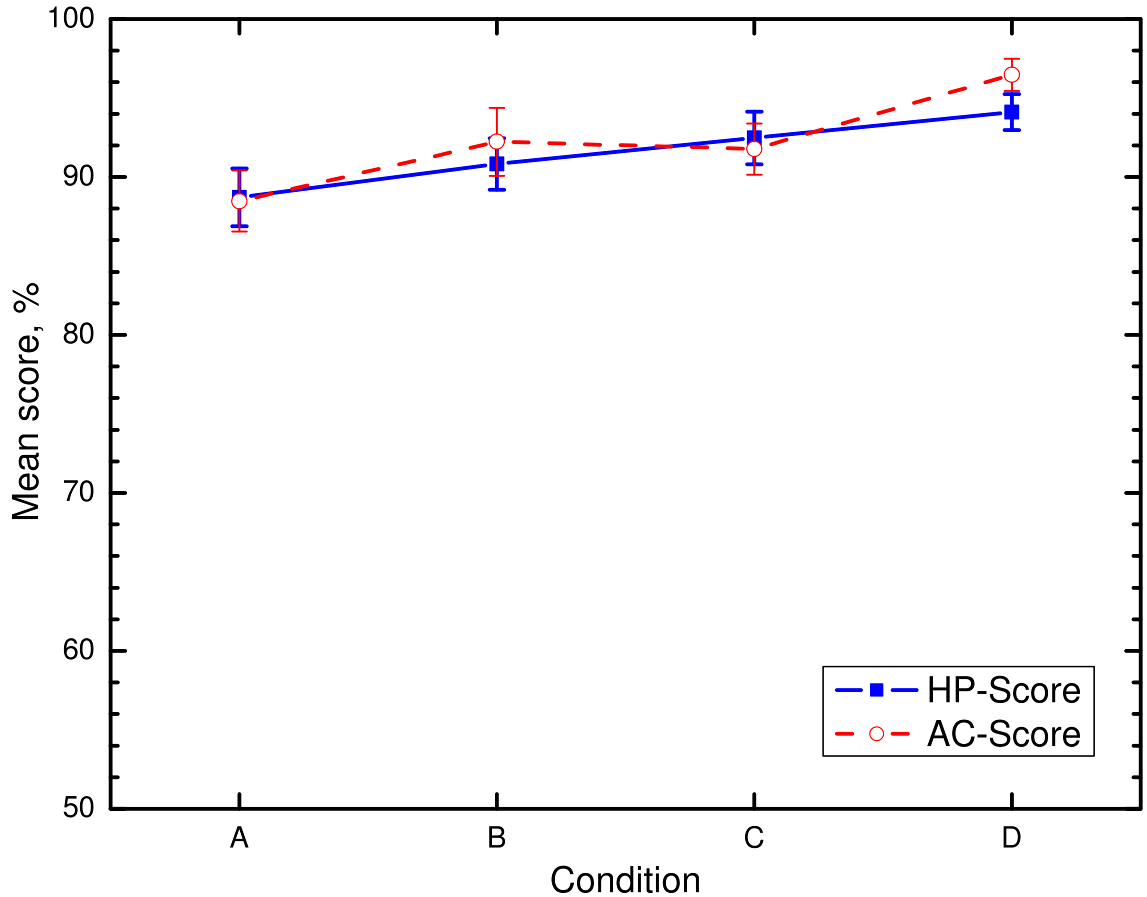
4000 Hz
2000 Hz
1000 Hz
500 Hz
C50, dB
C50, dB
C50, dB
C50, dB
T60, s
15
10
5
0
-5
-10
1
2
3
4



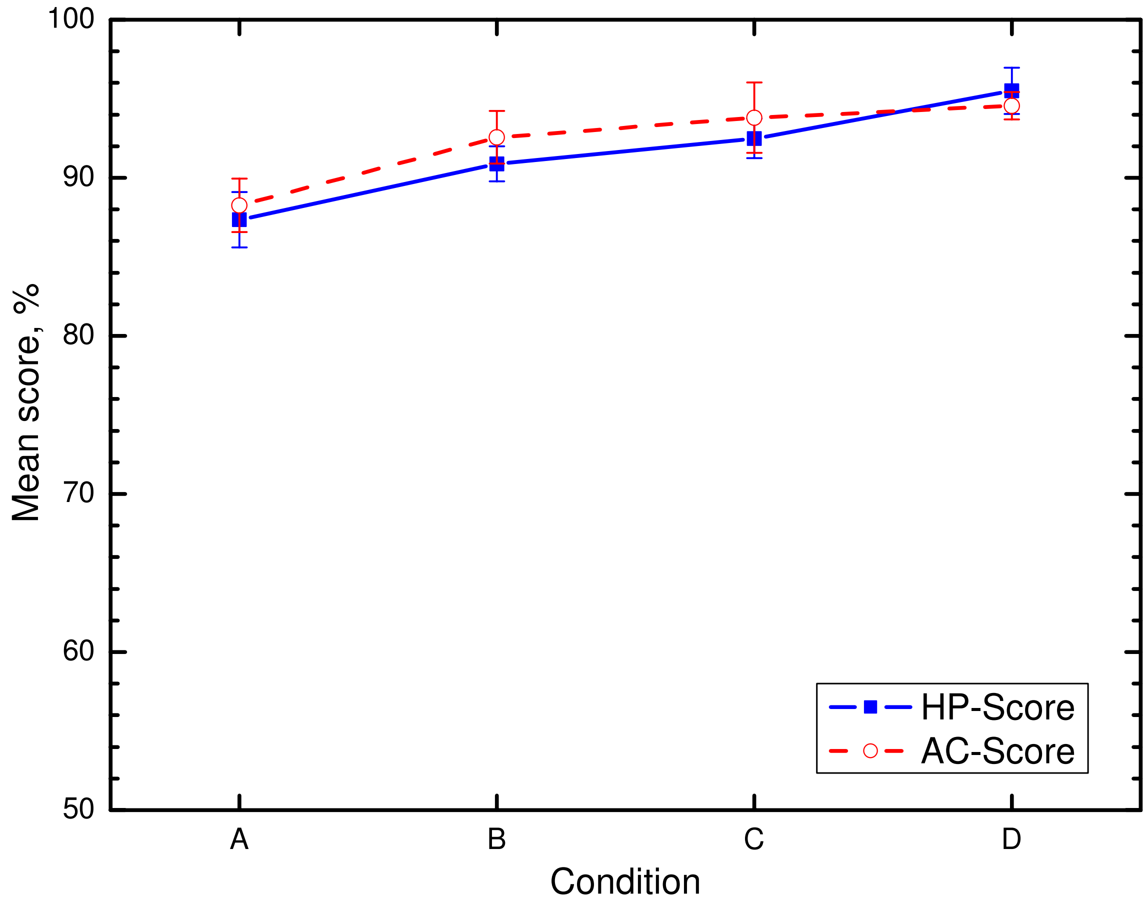
30
25
20
15
10
5
0
G(500,1k), dB
0.0
0.5
1.0
1.5
2.0
EDT(500,1k), s



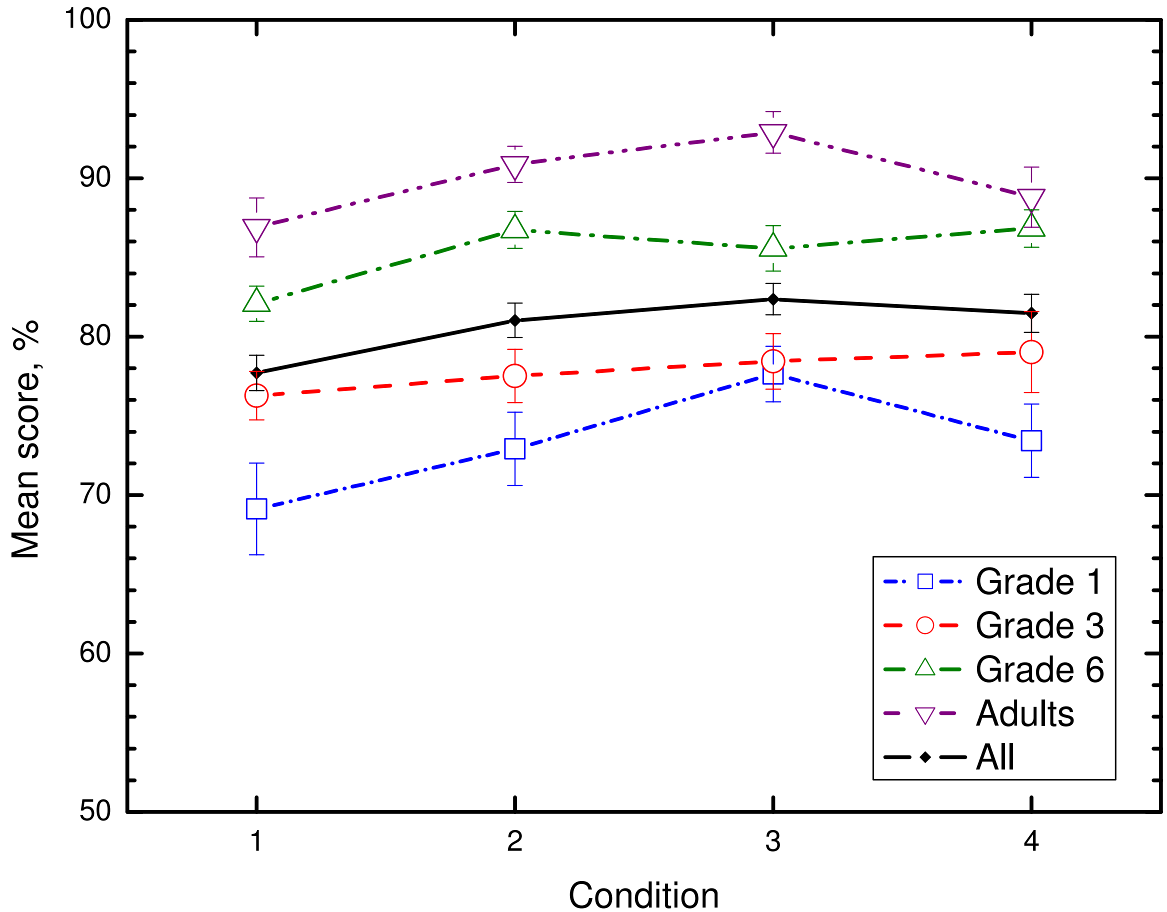
T60 = 0.3 s
L
R
T60 = 0.6 s
L
R
T60 = 0.9 s
L
R
T60 = 1.2 s
L
R
AC-HP Level difference, dB
0
5
10
125
250
500
1000
2000
4000
8000
Frequency, Hz

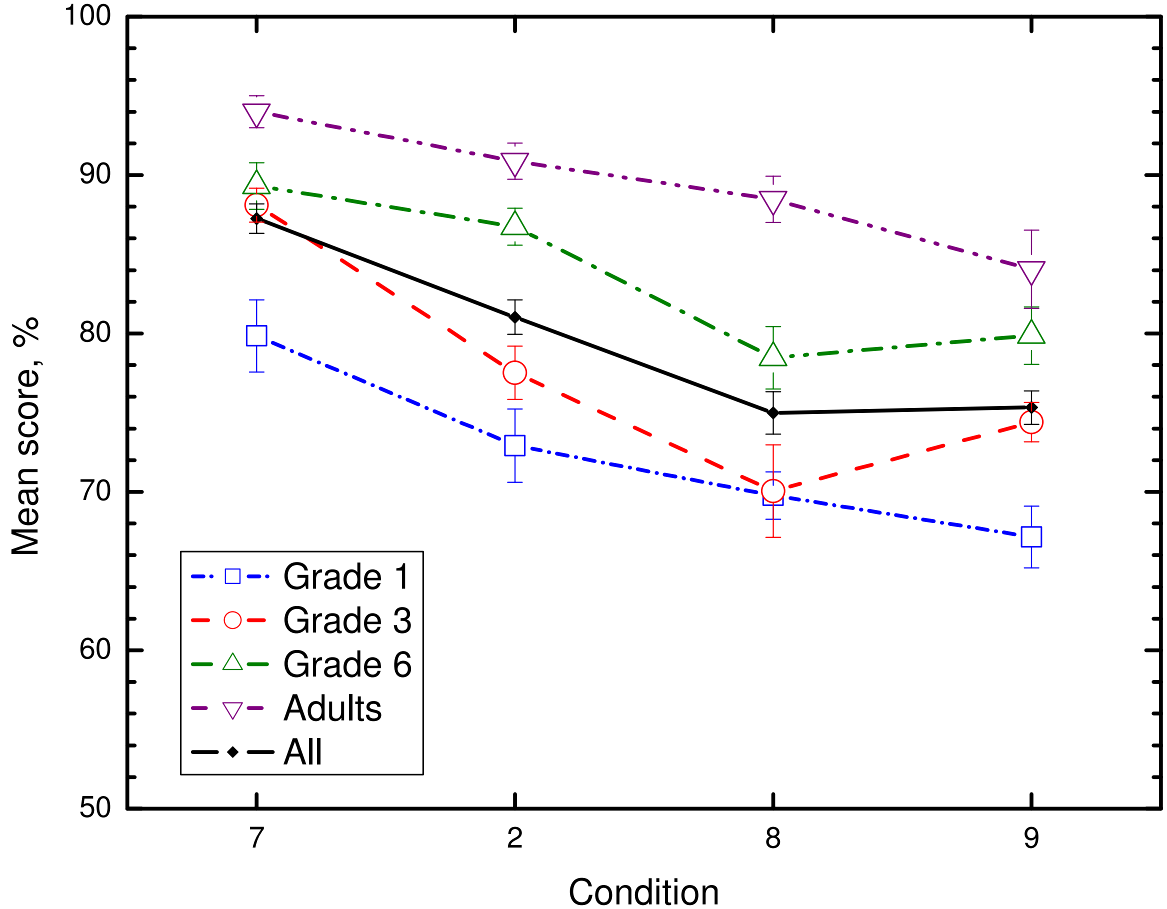


100
90
80
70
60
50
Mean score, %
A
B
C
D
Condition
HP-Score
AC-Score

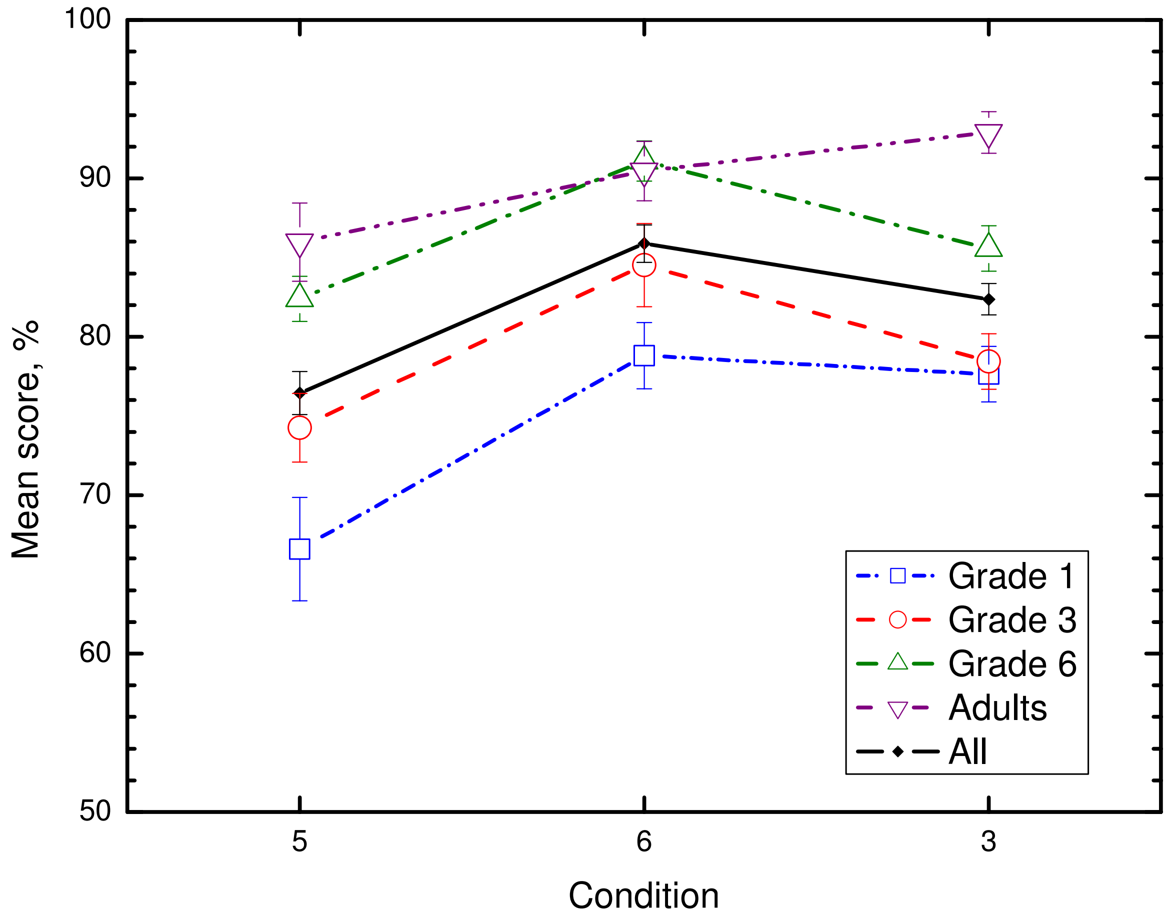


100
90
80
70
60
50
Mean score, %
A
B
C
D
Condition
HP-Score
AC-Score

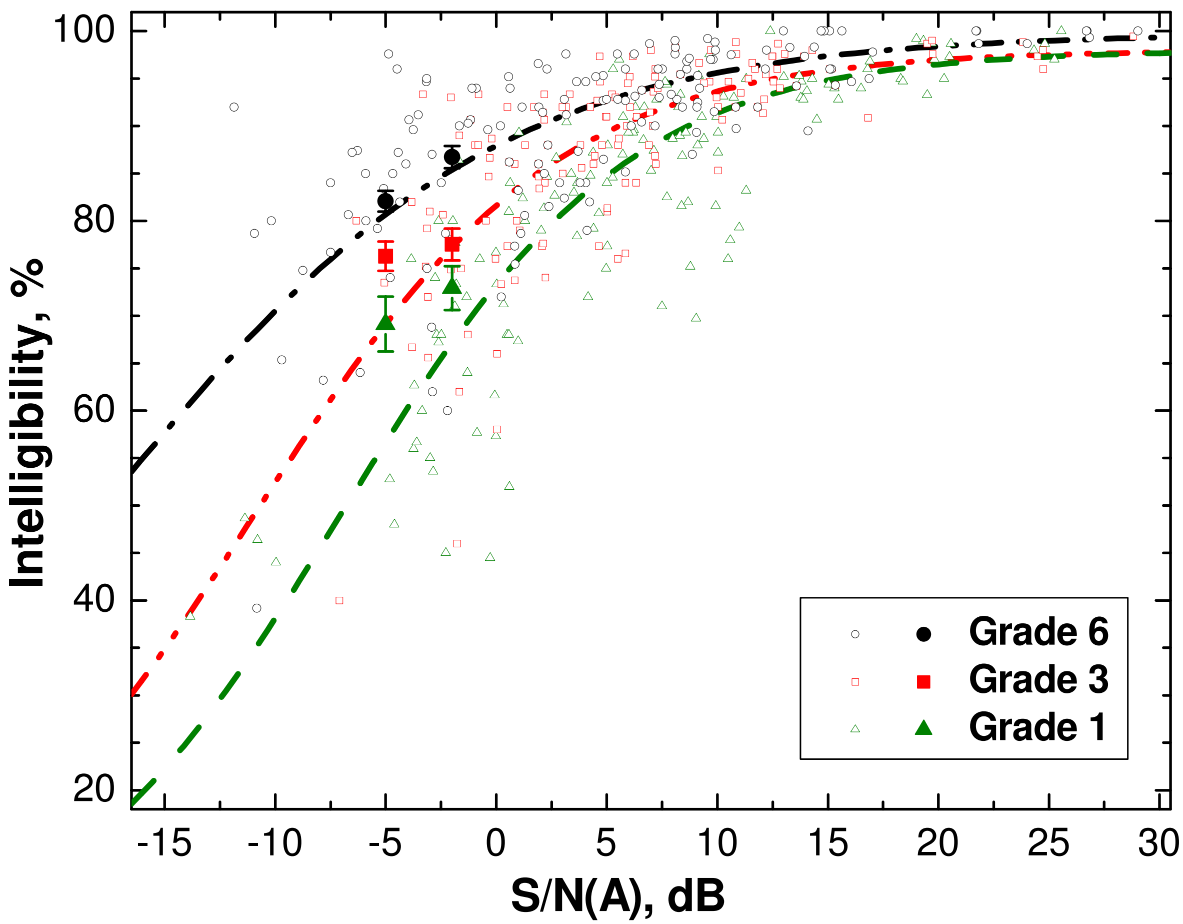

100
90
80
70
60
50
Mean score, %
1
2
3
4
Condition
Grade 1
Grade 3
Grade 6
Adults
All



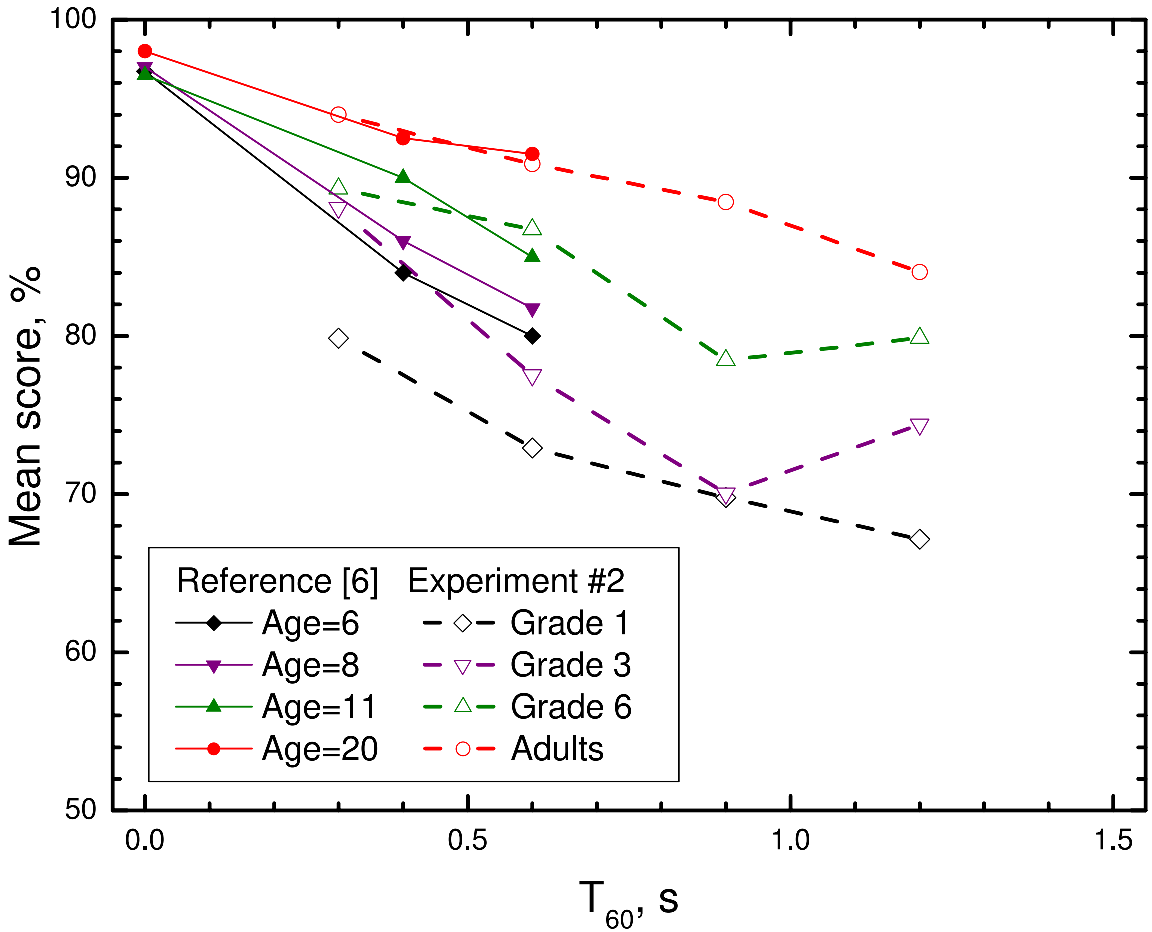
100
90
80
70
60
50
Mean score, %
7
2
8
9
Condition
Grade 1
Grade 3
Grade 6
Adults
All



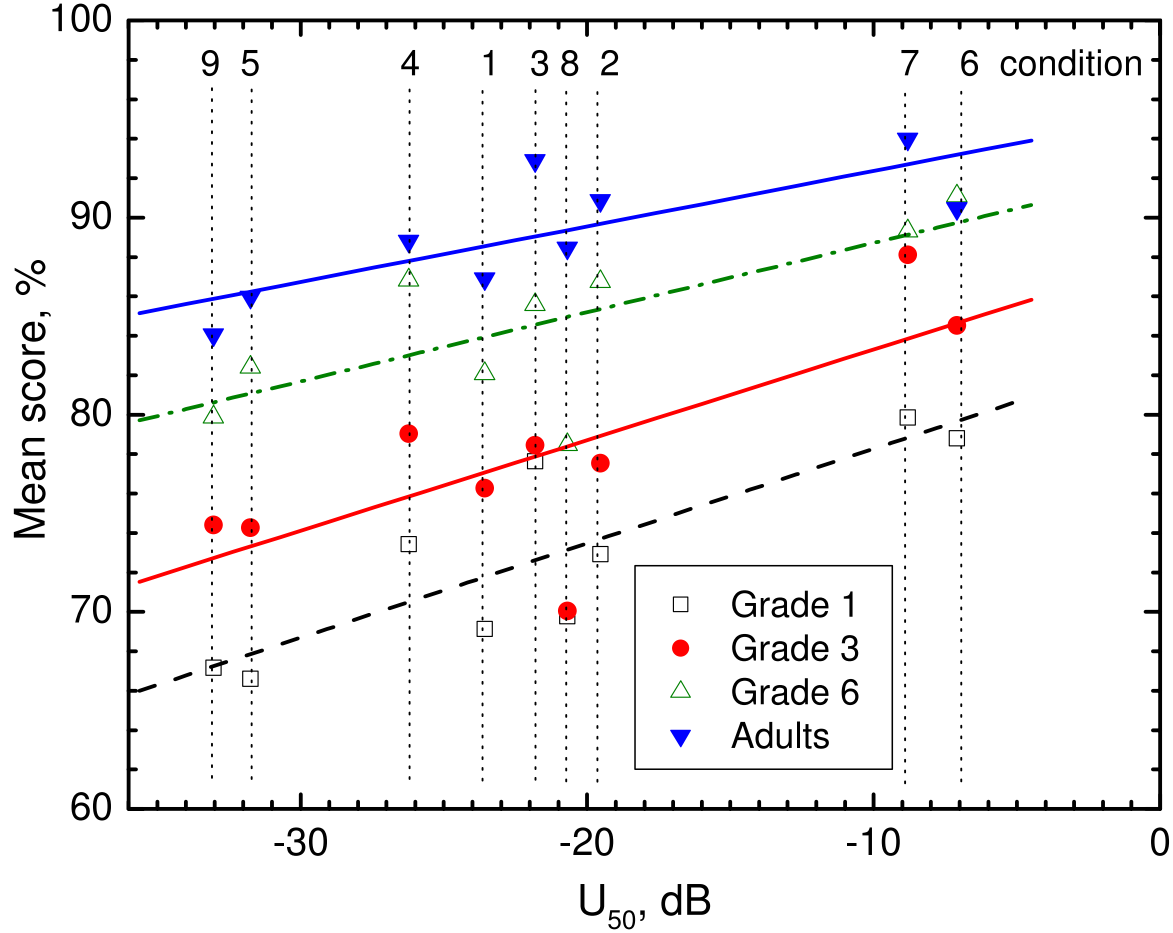
100
90
80
70
60
50
Mean score, %
5
6
3
Condition
Grade 1
Grade 3
Grade 6
Adults
All



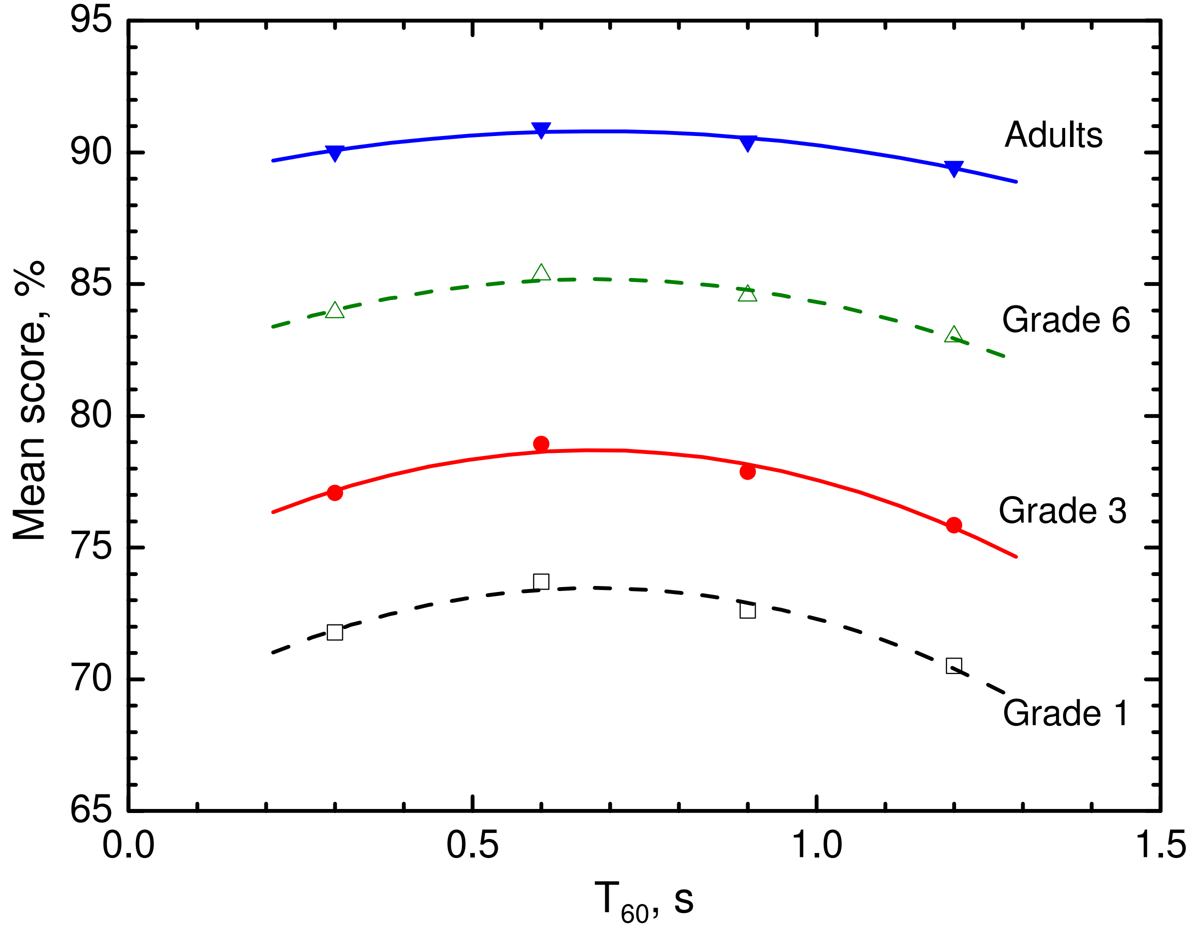
Intelligibility, %
S/N(A), dB
100
80
60
40
20
-15
-10
-5
0
5
10
15
20
25
30
Grade 6
Grade 3
Grade 1



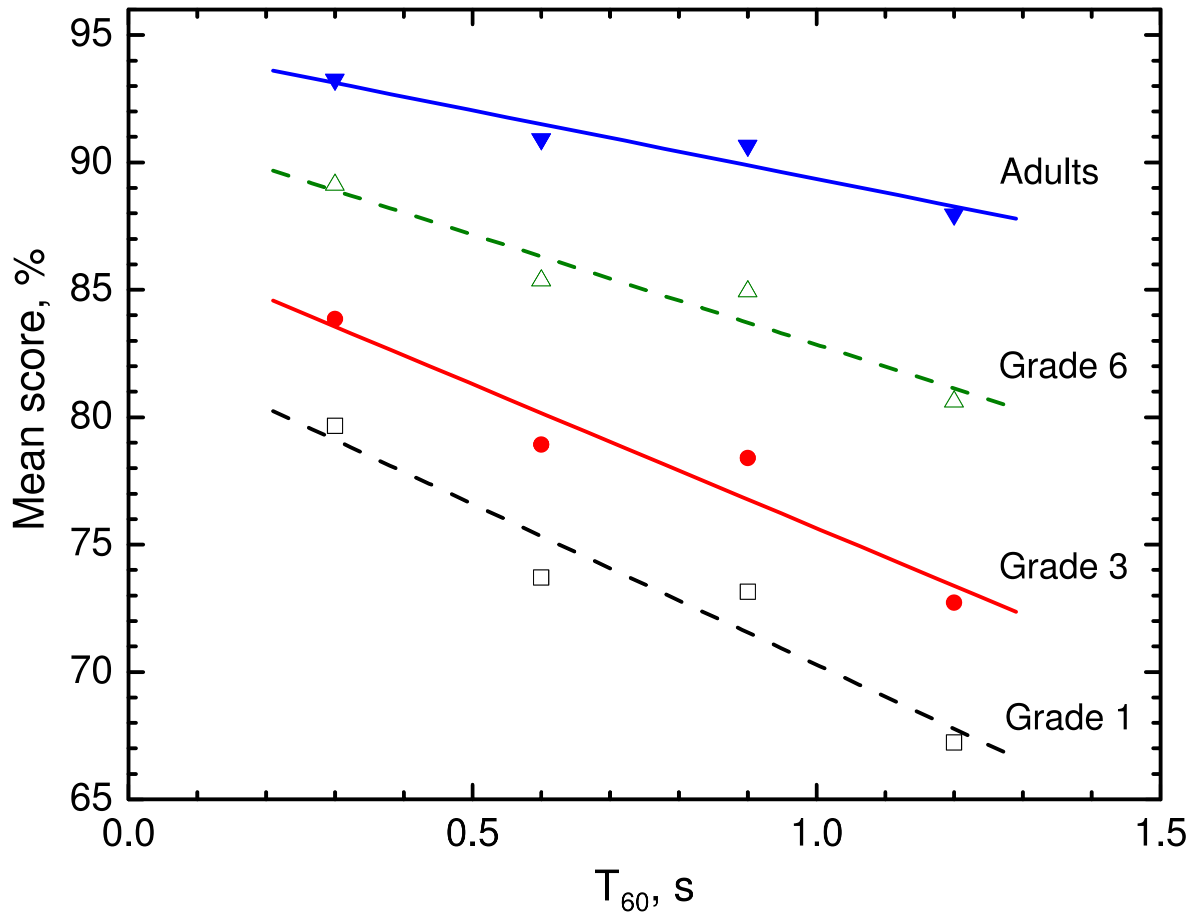
100
90
80
70
60
50
0.0
0.5
1.0
1.5
Mean score, %
T60, s
Reference [6]
Experiment #2
Age=6
Age=8
Age=11
Age=20
Grade 1
Grade 3
Grade 6
Adults



100
90
80
70
60
9
5
4
1
3
8
2
7
6
condition
Mean score, %
Grade 1
Grade 3
Grade 6
Adults
-30
-20
-10
0
U50, dB



95
90
85
80
75
70
65
0.0
0.5
1.0
1.5
Mean score, %
T60, s
Adults
Grade 6
Grade 3
Grade 1



95
90
85
80
75
70
65
0.0
0.5
1.0
1.5
Mean score, %
T60, s
Adults
Grade 6
Grade 3
Grade 1