Classroom Acoustics II

ACOUSTICAL BARRIERS TO LEARNING

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A publication of the
Technical Committee on Speech Communication
of the Acoustical Society of America

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Acoustical Barriers to Learning

"Speech produced in one place in a room should be clear and intelligible everywhere in the room." (Nabelek and Nabelek, 1985)

This simple statement defines a classroom with no acoustic barriers: a well-designed learning space with low noise levels and minimal reverberation or reflections. Many U.S. classrooms are not free of acoustic barriers to learning. It is not possible to provide an appropriate education in excessively noisy and reverberant rooms. Students and teachers need rooms with good acoustics so that acoustic barriers to learning are removed. To this end, the American National Standards Institute (ANSI) has approved a standard for maximum levels of classroom noise and reverberation (ANSI S12.60-2002. Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools).

Why do schools need quiet learning spaces for their students and teachers?

- Because students under age 15 are still developing mature language and need appropriate listening environments to understand the spoken message
- Because many learning spaces serve students with disabilities: learning disabilities, language learning problems, behavior problems, reduced cognitive skills, hearing loss, auditory processing disorders and chronic illnesses. These students have a special need for classrooms that allow clear listening and communication
- Because teachers should be able to use a natural teaching voice free from vocal stress
- Because many schools offer adult learning activities and adult learner groups can include persons with hearing loss, learning disabilities, and chronic illnesses

Why now?

In this century's early decades, thousands of aging schools will be replaced or renovated. According to the U.S. General Accounting Office (1995), one-third of the nation's schools need major renovation or replacement. Furthermore, census projections indicate that over 400,000 additional students will enter our schools each year for the next 50 years. This growth means we will need about 16,000 new classrooms each year. It is much less expensive to design new buildings with good acoustics than it is to fix the problems afterward. For example, heating, ventilating and air-conditioning (HVAC) systems are common sources of noise in classrooms. Installing quiet systems makes good sense, as renovating HVAC systems to achieve quiet levels may be prohibitively expensive. (For additional information, see Schaffer, 1999).

What is the problem?

Schools are places of learning where speaking and listening are the primary communication modes. Until recently neither school planners nor the general public were aware of the significant negative effect of noise and excessive reverberation on the learning process. The large body of research describing this problem is making everyone more aware of the importance of good acoustics. Parents have been instrumental in increasing this awareness, filing petitions with their school districts and the U.S. Access Board (www.access-board.gov).

Many learning spaces are poor listening places because of:

- Noise from outside the building, such as from aircraft and vehicular traffic
- Noise generated by heating, ventilating, and air conditioning systems
- Noise emanating from hallways, adjacent spaces and the re-emergence of open school architecture (large rooms with partitions dividing the room for multiple classes)
- Computer and projector machine noise from inside the room
- The presence of too many hard, reflective surfaces in the room causing excessive reverberation

What is the solution?

Local communities should recognize the need for good acoustics, based on the evidence summarized below, and should make this a priority when planning school construction. New and renovated schools should be built with reduced background noise and reverberation levels according to ANSI S12.60 so that all students in every new classroom will have clear auditory access to the spoken word in that classroom.

Introduction to the evidence

There is substantial evidence that children in classrooms require more favorable acoustic conditions than are currently found in most U.S. schools. Studies summarized below demonstrate that children need the following:

- An acoustic signal (the target spoken voice) that is at least 15 decibels (dB) more intense than the level of the background noise throughout the room
- Overall sound levels (including the target speech plus noise) that are no greater than 70 dBA throughout the room, as measured using a sound level meter set to its A-weighted scale
- Background noise that is less than 35 dBA throughout the unoccupied room
- Sound absorbing materials such as acoustic tiles that minimize reverberation, resulting in reverberation times of less than 0.6 seconds in unoccupied classrooms

Evidence shows that children need these conditions for learning because of the following factors:

- Young children are ineffective listeners for speech in noise until they reach adolescence, when they achieve levels of speech understanding similar to those of adults.
- Young children do not effectively listen and understand speech in reverberant conditions.
- Children are especially susceptible to ear infections (otitis media) in which middle-ear fluid causes hearing loss for weeks or months following an infection.
- Many children (up to 20% of the school population) have permanent hearing loss, as a result of congenital, genetic, and environmental causes. All people with hearing loss are adversely affected by both background noise and reverberation.
- Significant numbers of children are learning in a language not spoken in their homes. According to a U.S. Census Bureau report (1990), 2.5 million school-aged children had limited proficiency in English, comprising between 5% and 11% of all school-aged children. All people listening in a non-native language are susceptible to interference from background noise.
- Many children have difficulty focusing their attention on speech in background noise, even though they have normal hearing sensitivity and are learning in their native language. These students have auditory attention and learning problems, and make up an estimated 10–15% of the student body.

Evidence also shows that noisy classrooms require teachers to speak at vocal levels that cause stress and fatigue to their voices. Many teachers complain of tired voices, vocal strain, and health concerns because of their need to speak at such high vocal levels. In quieter classrooms, teachers can speak at more comfortable levels and their voices can still be heard throughout the room.

Despite these well-documented needs, American classrooms are often noisy and reverberant. In some classrooms, room amplification systems have been applied as a partial solution for rooms with poor acoustics. Although room amplification systems can increase the signal level of a speaker's voice, they increase overall sound levels and provide only a partial solution to the problem of excessive noise and reverberation in active learning situations.

The classroom acoustics standard focuses on solving the problems of excessive noise and reverberation at their sources, i.e., reducing reverberation and noise levels in classrooms. The goal of this standard is to maximize the acoustics of classrooms so that all talkers in a classroom can be understood by all listeners in that room. This can be accomplished by reducing background noise to 35 dBA in an unoccupied room and by controlling reverberation time to a maximum of 0.6 seconds. When classrooms meet the ANSI S12.60 standard criteria, communication will occur at a clear signal-to-noise ratio (SNR) of +15 dB (that is, the target speech signal is 15 dB louder than the background noise). In those classrooms, virtually all students and staff have full auditory access to the spoken message.

The evidence

Adults have sentence thresholds of about –4 dB signal-to-noise ratio, or SNR, and understand familiar sentences perfectly at 0 dB SNR. Young children, children with hearing loss, children learning a second language, and children listening in reverberant rooms require a higher signal-to-noise ratio in order to understand the spoken message.

Young listeners

Many studies over several decades have demonstrated that young listeners perform more poorly in noisy situations than do adults. Soli and Sullivan (1997) reported that understanding in noise is not completely developed until a child reaches adolescence. They studied children using the Hearing-in-Noise-Test (HINT) (Nilsson et al., 1994) and determined that the children's ability to understand sentences in noise improves through the early childhood years, reaching adult performance levels during the teen years (see Figure 1). Adults (shown here as the dark filled square) have sentence thresholds when the noise level exceeds the speech level by 4 dB (SNR of –4 dB). Children of varying ages required 1 to 4 dB more favorable signal-to-noise ratios, with the youngest children requiring the lowest noise levels.

Stelmachowicz et al. (2000) studied typically developing children ages 5–7 years, presenting words at different intensities, thus varying the audibility of the words (see Figure 2). Children's word understanding is shown in grey and striped bars; adult word understanding is shown in black bars. At high audibility levels (AI=0.8), both children and adults understood virtually all of the words. At low audibility levels (AI=0.2), adults could understand the majority of the words, but children understood very few.

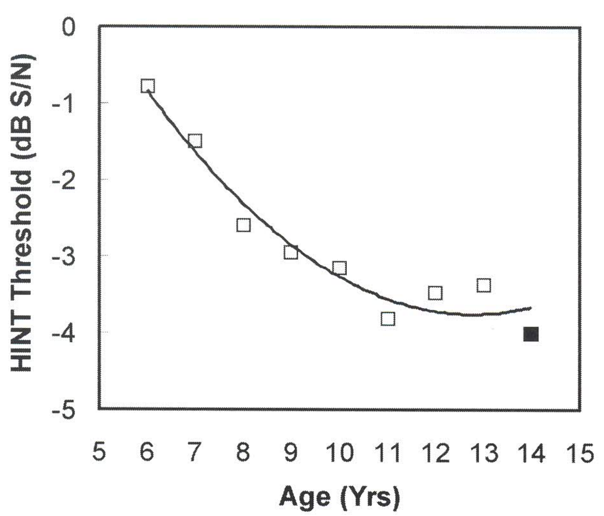
Similarly, Elliott (1979) studied 9- to 17-year-old children's recognition of sentences in noise. The performance of 9-year-olds was significantly poorer than that of 11-year-olds, who performed significantly poorer than 15- and 17-year-olds. Werner and Boike (2001) recently demonstrated that young children are inefficient listeners. They do not demonstrate a focus of attention on the critical frequency regions that differentiate the signal from the background noise. The overwhelming evidence presented in these studies suggests that young children are less sophisticated listeners in background noise than are older children and adults.

There is also convincing evidence that young children do not fully understand speech in reverberant rooms. Litovsky (1997) has studied children's auditory development by examining changes in their precedence effect. The precedence effect refers to one's ability to suppress echo-like sounds that arise from sound bouncing off reflective surfaces. Adults perceive a single unified sound in reverberant rooms, suppressing most echoes that might interfere with speech understanding. The ability to suppress the echoes from reflective surfaces makes it easier to locate the actual sound source and thus improves speech understanding. The precedence effect is apparently not present at birth, but emerges during childhood. Five-year-old children start to develop the precedence effect for simple sounds like clicks, but are much poorer than adults at processing the source and echo for complex sounds like speech. Litovsky showed that young children are able to localize single sounds as well as adults, but while adults are capable of suppressing echo information that is irrelevant, children are less able to do so. They apparently continue to hear some echoes as independent sounds, and thus their understanding in reverberant rooms is reduced. Echo suppression seems to be a sophisticated auditory skill that develops during childhood.

Johnson (2000) studied children ages 6 to 15 years for their understanding of consonants in noise alone, in reverberation alone, and in both noise and reverberation. Johnson found that 14-year-old children could identify consonants at adult-like levels in noise alone or in reverberation alone. However, in conditions of reverberation plus noise, children's perception of consonants did not reach adult levels until the late teen years.

Figure 1

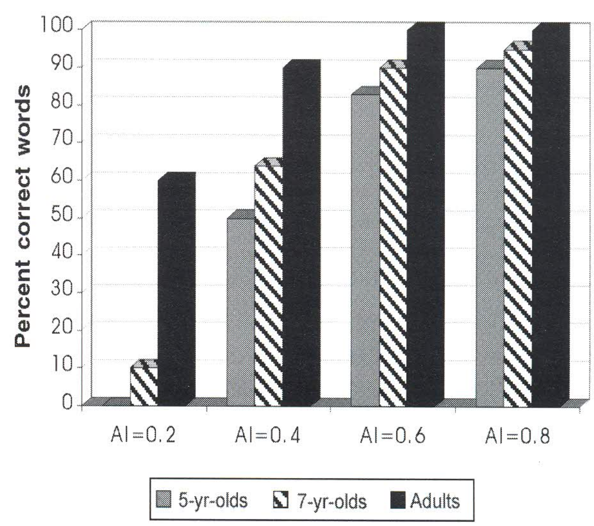
Developmental aspects of hearing in noise



Mean improvement in Hearing-in-Noise-Test (HINT) threshold is shown as a function of age for groups of normally developing children ages 6–13. Average adult thresholds are shown as a filled square.

Figure 2

Effects of audibility on children's understanding of words



The percent of words correctly repeated is shown for 5-year-olds (grey bars), 7-year-olds (striped bars), and adults (black bars). Test conditions ranged from low audibility, AI=0.2, to high audibility, AI=0.8. (adapted from Stelmachowicz et al., 2000)

Children learning English as a second language

The ability to understand spoken English in noise is also related to the listener's proficiency in the English language (see Figure 3). Eleven-year-old children who were speakers of other languages performed significantly more poorly on the HINT test than did age-matched children who were native speakers of English (Gelnett et al., 1994). Children whose first language was English (shown in open diamonds) understood sentences at –4 dB SNR. Children whose first language was not English required SNRs of +1 to –3 dB. Those children with poorer English vocabulary required the most favorable conditions. Nevertheless, all children who are less experienced in English require more favorable conditions for understanding classroom conversations.

Across the U.S., major metropolitan areas are reporting that 20% or more of their school children speak languages other than English at home (U.S. Census 1990). For example, in the early grades, 50% of children in the Los Angeles Unified School District speak languages other than English at home. In our increasingly diverse nation, multi-lingual families will become more common, even in smaller communities.

Children and ear infections

Young children are especially susceptible to temporary, recurring middle ear infections that are often accompanied by fluid in the middle ear (effusion) that causes hearing loss. The incidence of effusion among children is at an all-time high, having *doubled* between 1975 and 1990 (Schappert, 1992). Middle ear infection is the most common medical diagnosis for children, accounting for 6 million office visits in 1990 for children between the ages of 5–15 years (Stoll and Fink, 1996). Many ear infections are invisible and symptom-free, and may go unnoticed. Only half of the infections clear up within a month, whether treated or not. During that time, a month or more, the child's hearing loss fluctuates, varying between 0 to 40 dB (normal to mild hearing loss). Stoll and Fink (1996) estimate that if there are 32 children in a first-grade class, during one school year there may be 24 bouts of ear infections, averaging 3–4 weeks each. Logically, every week there are children with hearing loss resulting from middle ear problems. These young students may not be aware of their hearing loss and will not know to ask for repetition or help.

Children with permanent hearing loss

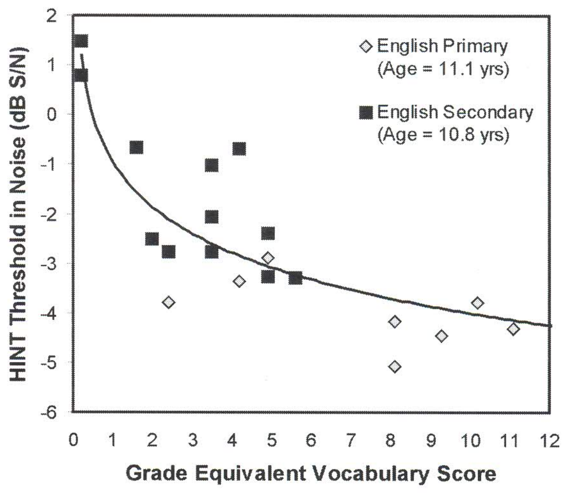
In addition to the evidence regarding ear infections, three recent studies have uncovered surprising numbers of children with slight, permanent hearing loss. In contrast to temporary hearing loss caused by ear infections, permanent hearing loss is almost always sensorineural, linked to damage in the sensory cells of the inner ear or auditory nerve. Sensorineural hearing loss is more than a simple attenuation of the intensity of sound. Sounds are not just quieter, they may also be distorted by a damaged auditory system. Hearing aids and other amplifying devices cannot fully overcome the distortion. Sensorineural hearing loss is usually caused by disease, genetics, drugs, excessive noise or a combination of these factors.

Niskar et al. (1998), from the Centers for Disease Control and Prevention, studied 6000 children and adolescents, ages 6–19 years. They found that 15% of these students had some hearing loss of at least 16 dB. A more recent study from that group (Niskar et al., 2001) has shown that 12.5% of school-aged children (approximately 5 million) have some hearing loss caused by excessive noise.

Bess et al. (1998) found that 13% of their sample of 1200 children in Tennessee had slight (15 to 25 dB) hearing loss. They also documented the educational consequences of these slight losses. Surprisingly, 37% of the children with slight hearing loss had repeated at least one grade in school, compared with only 3% of the control group of matched peers. The children with slight hearing loss were usually unaware of their loss, yet they exhibited significantly greater dysfunction than children with normal hearing on several tests of behavior, energy, stress, social support and self-esteem.

Figure 3

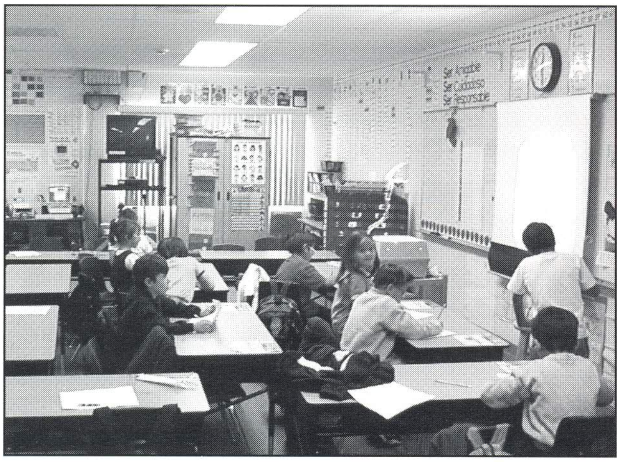
Effects of inexperience with English language



Individual Hearing-in-Noise-Test (HINT) thresholds are shown as a function of grade equivalent vocabulary scores for children who were a) speakers of English as their primary language (open diamonds), and b) speakers of English as their secondary language (filled squares).

Figure 4, panels a through c

Examples of intrusive noise in classrooms



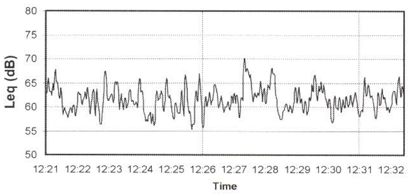


Figure 4a. A typical second-grade class is shown. The 17 students are working quietly and independently, and the teacher is roaming throughout the room, assisting students. A time trace from the sound level meter shows the level of sound occurring over a 10-minute period. The trace shows a background noise level ranging from 59 to 62 dBA that apparently arises from the steady output of the HVAC system. The teacher's voice is measured at 60–62 dBA, resulting in a signal-to-noise (SNR) ratio of 0 dB. At that SNR, we can expect that children of this age are missing significant portions of the teacher's message.

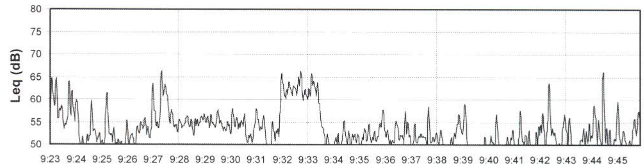
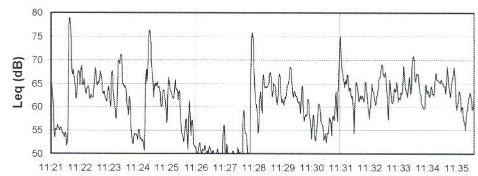
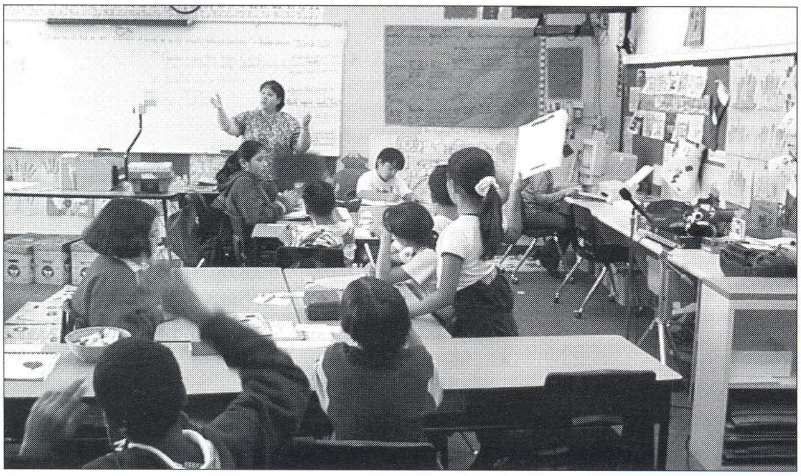
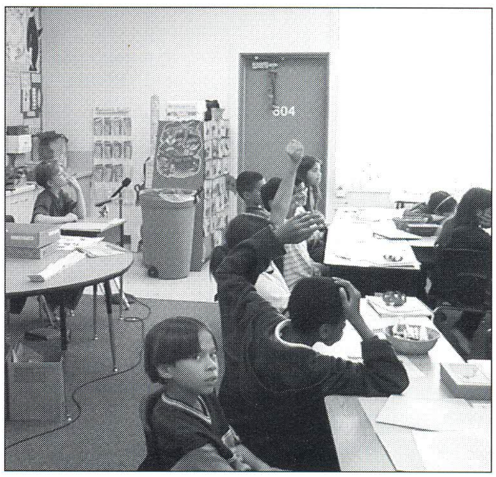


Figure 4b. A fourth-grade class of 25 students is shown. The students are taking an exam in a room that has a partition at the back. Behind the partition is another fourth grade class. From the time trace, one can see that the overall noise levels are low during the exam (50–56 dBA), with the exception of some bursts of noise that arise from the adjacent class. At times the noise coming through the partition exceeds 65 dBA. During those times, it would be easy for the students to become distracted by the clearly audible activity in the adjacent classroom.

Figure 4c. A fifth-grade class of 26 students is listening to a teacher lecture. The teacher's voice averages 60 dBA, the same overall level as the average background noise, again causing students to miss significant parts of the teacher's message. Occasional bursts of noise through the hallway door exceed 75 dBA, causing momentary coverage of the teacher's voice.







Children with auditory learning problems

Recent neurobiological research has shown that children with learning problems experience difficulty understanding speech sounds in noise. Cunningham et al. (2001) measured brain responses to speech sounds that are often confused ("da" and "ga"). The children with documented learning problems were no different from typical children in their discrimination of "da" and "ga" in quiet. They were, however, poorer than other children in their discrimination of the sounds in noise. The brain responses from the children with learning problems showed reduced neural precision and did not faithfully convey the representation of the noisy speech sounds to the brain. These results support the general impression that background noise causes excessive difficulty for children who have learning disabilities and attention deficit disorder.

Noisy and reverberant classrooms

Classrooms are generally noisy places, and children are more active than in past decades. Knecht et el. (2002) measured reverberation and background noise levels in 32 unoccupied elementary classrooms in eight public school buildings in central Ohio. Background noise levels ranged from 32 to 67 dBA. While the noisiest classrooms were those with noisy heating, ventilating and air-conditioning (HVAC) units running, most of the classrooms were noisy even when the HVAC systems were turned off. Significant noise was measured from other internal equipment and from intrusions from hallways and outdoors.

Sample recordings of classroom noise levels are shown in Figure 4a through 4c. Full descriptions of the activities are found in the accompanying captions. Overall, these examples show excessive noise from HVAC units, from adjacent classrooms through temporary partitions, and from hallways through ill-fitting classroom doors. These types of noise intrusions occur frequently and are typical of classroom situations.

Reverberation in classrooms arises from sound reflecting off of hard walls and high ceilings. In rooms with hard surfaces, sound reflects, causing a persistence of the sound after the source itself stops. Excessive reverberation "smears" the temporal properties of speech signals. Instead of individual distinct speech sounds following one after another in words, the reverberation makes the sounds overlap each other, causing them to be more difficult to understand. Figure 5 shows the spectrogram of a phrase ("breakfast is ready") in non-reverberant conditions in the upper graph and in moderately reverberant conditions in the lower graph. In the upper graph, one can see the various consonants as the voice pauses to form the /k/ and the /d/. In the lower graph, one can see that the reverberation, although moderate, has caused the vowels to "smear" over the consonants, eliminating the pauses and causing the consonants to be more difficult to recognize. Reverberation time (RT) in rooms is measured in terms of the time required for the sound of a signal to be reduced by 60 dB, once the sound has stopped. In highly reverberant rooms (RT>2 seconds), such as in a cathedral or large hall, an audible echo is present and speech understanding is diminished. Favorable RTs for understanding speech range from 0.2 to 0.6 seconds for classrooms.

Reverberation time measurements for the 32 classrooms in the Knecht et al. study (2002) ranged from 0.2 to 1.27 seconds. Only four of the classrooms had RTs less than the desired 0.6 seconds. Because of the combination of the observed noise levels (32 to 67 dBA) and RTs above, teachers' voices are often reaching students at unacceptably low SNR, and the undesirable reverberation further confounds intelligibility.

Some schools have investigated the use of amplification devices to increase teachers' voice levels above the excessive background noise. This might seem sensible when the teaching style is primarily a lecture format. Most younger students are in classes where that is not the case. In addition, other evidence demonstrates clearly that listeners do not understand speech well when overall sound levels exceed 69 dBA (Studebaker et al., 1999). As sound levels increase above 69 dBA, all listeners require more favorable SNRs in order to maintain full understanding of the speech. Clearly, then, it is more desirable to reduce background noise and overall sound levels than it is to amplify sound above the already high levels of background noise.

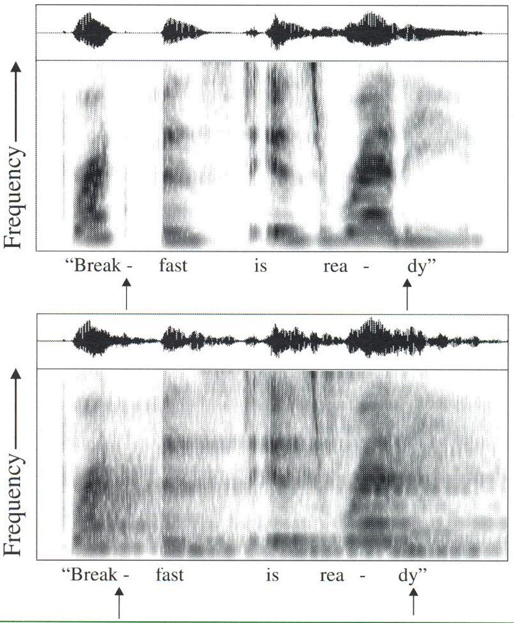


Figure 5. An example of a phrase ("breakfast is ready") in non-reverberant (upper graph) and in simulated moderately reverberant (lower graph) conditions (RT=1 second). Each graph shows the time waveform at the top of the panel, and the spectrogram, or change in frequency of the sound over time, at the bottom. Darker patterns indicate more intense sounds; light areas indicate silence or quiet sounds. Note that even with moderate reverberation, many of the temporal patterns of the speech are smeared. The quiet /k/ (shown with an arrow) is apparent in the upper graph but masked in the lower one. The second syllable in "ready" (shown with an arrow) is also masked by the reverberation.

Educational effects of reduced access to the acoustic signal

Classroom noise also affects other significant teaching/learning problems, including teacher vocal fatigue and students' off-task behavior. In one survey (Smith et al., 1998), 32% of teachers reported having occasional voice fatigue, and 20% reported they had missed work due to voice problems. These consequences, along with the learning deficits experienced by students in noisy rooms, are the costs of the current situation.

Students who do not have full auditory access to spoken information in classrooms (from the teacher or from peers) do not learn at a normal rate. The literature demonstrates that even slight hearing loss is often accompanied by delayed acquisition of vocabulary, reduced incidental learning, frequent significant academic delay, and limited reading abilities (e.g., Ross, 1990). However, none of these deficits is a necessary consequence of hearing loss. They are consequences, rather, of reduced communication opportunities between the child with hearing loss and that child's teachers and peers. If the acoustic barriers to communication can be overcome, then we can facilitate learning for all children.

Noise and reverberation control measures are needed to make American classrooms accessible to all students. Quiet, ducted HVAC systems are essential. Noise intrusion can be prevented by selecting building sites that minimize highway and aircraft noise. Further noise control can be achieved through appropriate installation of quality windows, doors and walls to prevent the intrusion of noise from adjacent spaces. Design guidelines such as these are contained in the classroom acoustics standard and in *Classroom Acoustics: a resource for creating learning environments with desirable listening conditions* (Seep et. al 2000). To make a cost-effective difference in classroom accessibility, school administrators need access to an interdisciplinary team of professionals to develop a cluster of solutions for good classroom acoustics.

History of the Standard's development

In mid-1997, a Working Group on Classroom Acoustics was commissioned by the American National Standards Institute (ANSI) to develop a draft standard for approval by the ANSI committee responsible for noise issues (S-12). This Working Group included audiologists, acoustic engineers, building managers, educators, interior designers, persons with hearing loss, architects, acoustical materials manufacturers, parents, professional organizations, consumer organizations and governmental organizations.

In September 1999 the U.S. Access Board published a "Notice of Agency Action on Classroom Acoustics" in the Federal Register. The Access Board is that part of the U.S. government that develops guidelines for use by designers and builders so that buildings can meet the requirements of the Americans with Disabilities Act (ADA). Title III of the ADA lists places of education as a public accommodation category. By publishing this notice, the Access Board recognized that noise and reverberation can be a significant barrier to listening and learning in the classroom. The ANSI standard was submitted to the ANSI Board of Standards Review for approval at the end of May 2002. It was approved on June 27, 2002. The Access Board has proposed this new ANSI standard on classroom acoustics to the Internal Code Council (ICC) as its guideline to meet ADA requirements.

How can this Standard help your schools?

The Classroom Acoustics Standard has both performance and design criteria for appropriate learning spaces. School leaders can use this standard:

- To understand some of the basic acoustic terminology
- To effectively communicate with architects, designers and planners during the process of defining and writing specifications for new and renovated buildings with good acoustics
- To create learning spaces where speech is spoken comfortably and understood easily because background noise will be softer than spoken words and reverberation/echo will be appropriate

Summary

The literature has demonstrated that if an acoustic environment can be provided that allows +15 dB signal-to-noise ratio throughout the entire classroom, then all participants can hear well enough to receive the spoken message fully. Classrooms that maintain ambient noise levels of 35 dBA or less will allow speakers' voices to reach all listeners at the desired +15 dB signal-to-noise ratio. In addition, research has shown that children require low room reverberation. The combination of background noise less than 35 dBA and reverberation times between 0.2 and 0.6 seconds in unoccupied rooms will allow full access to clear speech in our classrooms. This is a challenging goal, but it is the right and achievable goal for the acoustical design of all classrooms.

There are children in every class who, though totally unaware of it themselves, cannot hear or understand the spoken message well. This has a very significant impact on learning, attention, and especially reading. We need creative, inventive solutions to quiet our classrooms and reduce reverberation. These include architectural changes and quieter HVAC systems for better listening conditions. These solutions will come at some added expense now, but ultimately will prove to be a smart investment for our students and communities.

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Other overviews of issues related to classroom acoustics can be found in the following five comprehensive references. Additional references for specific topics can be found at the end of this document.

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