Clinical Forum

Ten Ways to Provide a High-Quality Acoustical Environment in Schools

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Reverberation time (RT), signal-to-noise ratio (SNR), and background noise level measurements have traditionally been used to describe classroom acoustical situations (Bradley, 1987; Crandell, Smaldino, & Flexer, 1995). Reverberation is often considered in negative terms. However, sound reflections can assist listeners for improved speech understanding and sound quality. Haas (1972) described the beneficial effect of sound reflections that arrive at listeners' ears within short time periods after the direct sound, thereby increasing the apparent loudness of the sounds.

The "useful-to-detrimental energy ratios" illustrated below were defined by Bradley (1985, 1986), Lochner and Burger (1961), and, more recently, Bradley, Reich, and Norcross (1999). The ratios are measurements based on impulse response techniques that can account for the beneficial effects of the loudness of the direct sound and the contribution of early sound reflections in speech signals simultaneously with the deleterious effects of reverberation and background noise in rooms. These measures relate the useful (or signal) portion of energy in speech, consisting of the direct sound and early reflections, to the detrimental energy (or noise), which consists of reverberant energy and background noise.

$$\frac{\text{useful energy}}{\text{detrimental energy}} = \frac{\text{direct sound + early reflections}}{\text{reverberant energy + background noise}}$$

ABSTRACT: The purpose of this article is to describe the use of impulse response measures and observations in Florida classrooms. As a result of measures and observations in "healthy" and poor acoustical environments, 10 practical recommendations are proposed for improving the acoustical environment in schools. The primary research for these recommendations consisted of recording acoustical measurements of reverberation time and background noise, as well as newer acoustical measurements based on impulse response techniques, in 56 actual classrooms. Observations of classroom situations occurred in a subset of these schools. Computer and physical models of eight classrooms were constructed and tested with varying room finish materials and background noise levels to study the combined effects of these architectural items on speech perception in the model rooms. The primary recommendations all relate to school design and planning. These include air-conditioning system selection and noise control techniques to minimize interference with listening, interior classroom acoustical design principles for maximizing speech perception, and the documentation of teaching methods and classroom arrangements that result in improving speech intelligibility and other factors affecting speech perception.

KEY WORDS: classroom acoustics, acoustical design, architectural acoustics, acoustical measurements, school design, speech intelligibility

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Bradley (1986) has shown correlations of 0.8 and higher, with a standard error of 9% between the useful-to-detrimental energy ratios' U50 and U80 measures and the scores on speech intelligibility tests taken by students in schools in Canada. The U50 is a useful-to-detrimental energy ratio with 50 milliseconds defined as the dividing point between the early energy that is useful and contributes to the loudness of the direct sound and the detrimental energy. Similarly, U80 defines 80 milliseconds as the dividing point between the useful and detrimental energy.

The speech transmission index (STI) proposed by Houtgast, Steneken, and Plomp (1980) synthesized this concept with a calibrated speech signal at transmission frequencies that were selected to represent those found in typical sequences of speech. Both the STI and the rapid speech transmission index (RASTI) are very closely related to speech intelligibility scores. A high STI or RASTI score for a room suggests that most listeners will be able to understand speech easily. Conversely, a low score suggests that many listeners will experience significant difficulty understanding speech in that room.

This innovation in conceptualizing and measuring classroom acoustic indices was not possible until Haas (1972) identified the phenomena from a psychoacoustic standpoint. Also, suitable instrumentation was needed to break down the reverberation period in a room into its constituent parts. These aspects consist of direct sound, early reflections, reverberant "tail," and background noise (Cremer & Muller, 1982; Veneklasen, 1970). The relatively new international standard, ISO 3382 (1997), for the measurement of RT in rooms is based on the pioneering work of Manfred Schroeder (1965), who defined a procedure to measure RT from the impulse response of a room. Once an impulse response is acquired, many additional acoustical measures, such as the useful-to-detrimental energy ratios and the STI, can be acquired to study the "fine structure of reverberation" (Cremer & Muller, 1982; Meyer & Thiele, 1956). The impulse response also presents the amplitude (or loudness), arrival time, frequency content, and direction of the direct sound and all of the subsequent reflections that travel from a sound source to a listener's location. Theories are just beginning to emerge about how the impulse response of a room relates the perception of speech sounds to the materials, shape, and other architectural features of rooms (Siebein & Kinzey, 1999).

THE IMPULSE RESPONSE

The impulse response, which represents the pulsing of a room caused by a single, loud sound, provides a convenient way to describe and measure acoustical situations in rooms. The impulse response obtained in a room describes sound transmission and sound reflections within that room. It is hypothesized that each syllable of spoken words excites the room in a similar way (Cremer & Muller, 1982). The impulse response will vary at each seat in a room because it represents the unique signature of sound that arrives from a given source to a specific listener. The contribution of the direct sound and reflections from each of the walls, the ceiling, and other architectural elements is depicted in the impulse response, as shown in Figure 1.

Figure 1 is organized with two columns. The column on the left shows the path of sound travel between the source and the receiver for the situation. The column on the right shows the impulse response as a graph of sound amplitude or loudness (in decibels) on the vertical axis plotted versus time (in milliseconds) on the horizontal axis. The figure starts at the top with no communication between the people. Just the background or ambient noise exists in the room. In the second sketch in the series, the person on the left speaks. The direct sound travels from the person speaking through the air to the listener. In the third sketch in the series, the reflected sound path from the ceiling is shown as it arrives shortly after the direct sound at a reduced amplitude due to its longer path length. The fourth sketch in the series shows sounds reflecting from the walls of the room. These reflections arrive after the ceiling reflection at a lower amplitude due to the increase in path length. If the reflected sounds shown in the third and fourth sketches arrive within 50 milliseconds of the direct sound, they are considered as useful energy adding to the apparent loudness of the speech sounds. The fifth (bottom) sketch in the series shows sounds that strike multiple surfaces in the room. It is the reverberant energy that persists for some extended period of time (the RT) after the direct sound. This is also the sound energy that is considered detrimental to speech perception.

As the architectural characteristics of a room are altered, the impulse response and the qualities of what people hear and how well they hear are also changed. The impulse response can be used as a basis for suggesting possible architectural approaches to the design of a room or to help determine which modifications can be made to an existing room (Barron, 1993; Bradley, 1983; Cremer & Muller, 1982; Siebein & Kinzey, 1999). The components of the impulse response described in Figure 1 are summarized in Table 1, with the corresponding aspects of classroom design that can be used to (a) improve the positive components of the impulse response and (b) reduce the negative aspects of the impulse response.

The use of the impulse response as an acoustical diagnostic tool is analogous to an electrocardiogram of a heartbeat that a physician might use to evaluate the health of a patient. By looking at the relative amplitude and timing of a sequence of pulses (like the series of peaks and valleys one observes on a cardiogram), the acoustical consultant can look at the amplitude and arrival times of a series of reflected sounds in a classroom. The consultant can then make diagnoses concerning the "acoustical health" of the room and recommend design changes to improve communication in the room (Siebein & Kinzey, 1999).

The impulse response can help to provide a conceptual understanding of the links between perceived acoustical qualities and the architectural features of rooms. Additionally, it is used extensively to characterize sound fields in computer models, scale models, and full-size rooms. Once the impulse response has been obtained, the information can then be translated into a virtual sound field. This

Figure 1. Concept diagram of the impulse response of a classroom, illustrating the constituent elements of background noise, direct sound, early sound reflections from the ceiling and walls, and reverberant "tail."

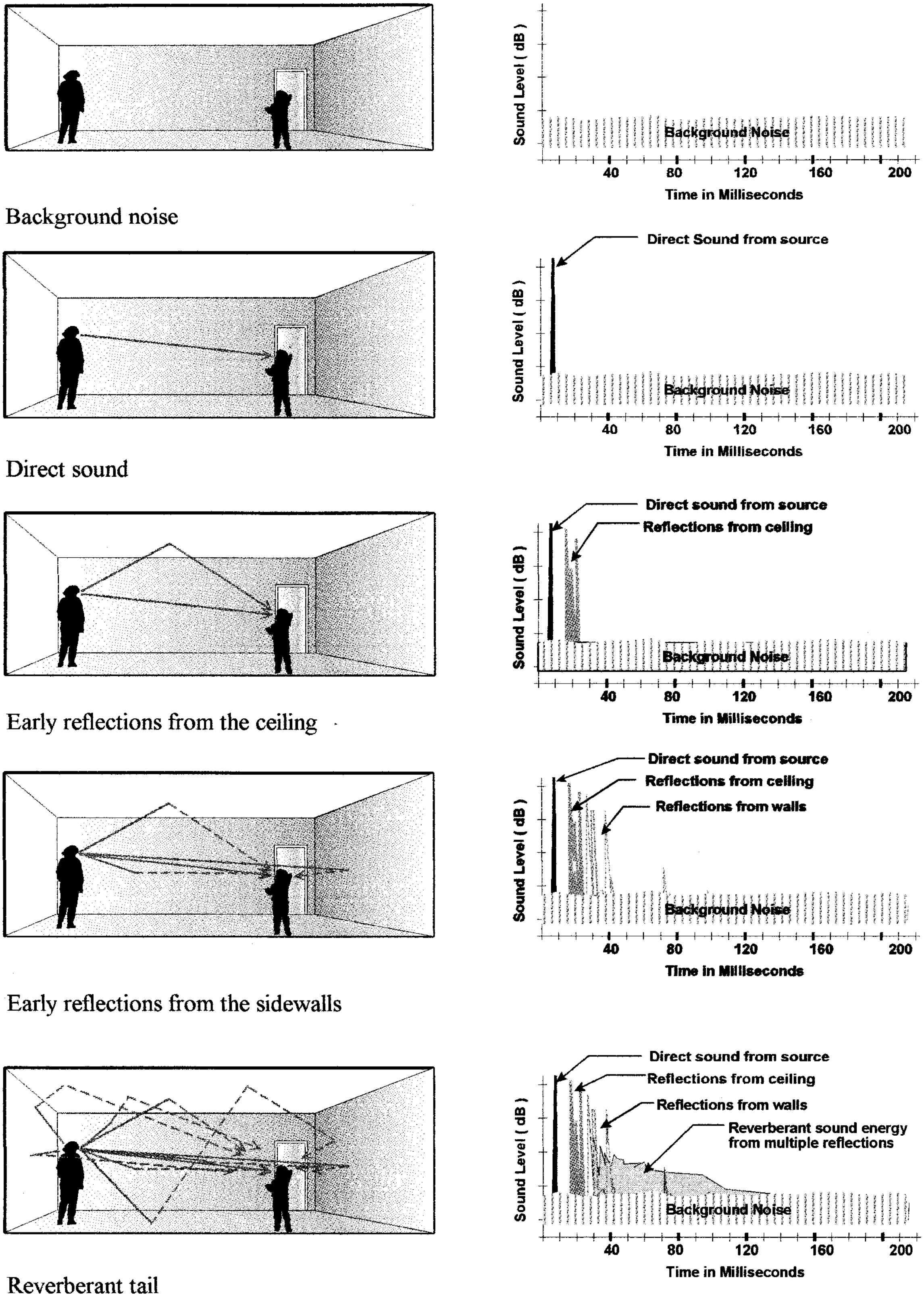


Table 1. Summary table of the four parts of an impulse response and the design strategies that are derived for typical classrooms.

Parts of the impulse response	*Strategies*	*Means*
Direct sound	Maximize	• Loudness of teacher's voice, diction, teaching methods, amplification
Early reflections	Maximize	• Strategically located sound-reflecting surfaces on the walls and ceiling near the teacher
Reverberant tail	Minimize, not eliminate	• Volume • Strategically located absorbent materials on the rear part of the ceilings and upper walls
Background noise	Minimize, not eliminate	• HVAC–system type and design • Site noises • Children in class • Children outside of class • Noises from adjoining rooms

makes it possible to actually hear how architectural changes to a computer model or scale model of a room that are indicated in the impulse response might be perceived by listeners in the room (Siebein & Kinzey, 1999).

The purpose of this article is to describe the use of impulse response measures and classroom observations in Florida classrooms. As a result of the measures and observations in "healthy" and poor acoustical environments, recommendations are proposed for improving the acoustical environments in schools.

COMPONENTS OF STUDY

The major components of the study completed to date are summarized in general terms below.

- Teams of researchers observed teachers and students in 10 classroom situations for time periods of 2–4 hours on each of 2–3 days.
- Acoustical measurements of RT and background noise (dBA and noise criteria [NC]) were made at multiple source and receiver locations in 56 different classrooms in 25 different schools located in 10 different school districts. More detailed impulse response measurements, including the STI, early to late sound index (C_{80}), relative strength (G), and other measures described in ISO 3382 for room acoustics measurements, were made in a smaller sample of 15 rooms using a TEF-20 analyzer or a WinMLS computer-based analyzer. Acoustical measurements of STI, G, C_{80}, RT, and background noise were also made for multiple source locations in two of the rooms so as to evaluate the acoustical effectiveness of the teaching methods (Gold et al., 1998).
- Physical and computer models of eight variations of typical classrooms were constructed to isolate variables and study the acoustical and architectural details of typical classroom situations.
- Team members designed a total of 54 school projects to understand the practical limits encountered due to limited budgets and competing demands in actual projects.

CHARACTERISTICS OF THE CLASSROOMS STUDIED

The rooms were selected to examine "typical" classrooms in Florida. Most of the schools were public schools that were constructed in suburban towns in the past 20 years. One of the schools was a private school. One was an older school for students with emotional and physical handicaps. The classrooms are representative of the acoustical conditions of the 722 similar rooms within the schools measured. If one includes the schools built using the same architectural designs in the school districts visited, the sample is representative of more than 5,000 classrooms.

Many of the classrooms were relatively similar to each other in room volume and interior finishes. The floors were carpeted in approximately 50% of the rooms. The ceilings were mostly acoustical ceiling tile with a noise reduction coefficient (NRC) estimated to be between 0.50–0.60. The NRC is the average sound absorption coefficient in the 250, 500, 1000, and 2000 Hz octave bands. Less than 20% of the rooms had a plaster or gypsum board ceiling. The walls were painted masonry in more than 75% of the rooms and were gypsum board in less than 25% of the rooms. One wall was typically an exterior wall that had windows from desk height to the ceiling. One of the classrooms had a sloping ceiling that was approximately 9 feet tall on one side and 18 feet tall on the other. Six of the rooms were portable classrooms. All of the rooms had some partial height furniture, such as bookshelves, to divide the room into smaller sections. The rooms also had student desks, tables, chairs, and a teacher's desk. Most of the ceilings were flat, with a height of between 2.5 meters (8.5 feet) and 4 meters (11 feet). The length and width of the rooms were slightly less than 10 meters (30 feet) (Gold et al., 1998).

IMPROVING THE ACOUSTICAL ENVIRONMENT OF CLASSROOMS

Several conclusions were made from our observations. First, the primary noise in classrooms was from heating, ventilating, and air-conditioning (HVAC) systems. Second, tall ceilings resulted in highly reverberant rooms. Sound-absorption material significantly reduced unwanted reverberation in these rooms. In addition, noise from tables, chairs, and children's feet added significant noise to the environment. Creative teachers were able to use effective strategies to improve the classroom SNR. Finally, some school sites were planned and chosen poorly.

Ten fundamental ways to improve the acoustical environment in classrooms are described next based on the measurements, observations, and computer models.

- *Carefully select and design the air-conditioning system for the school.* Classroom noise levels are directly linked to the type and design of the air-conditioning system used. There is a significant decrease in speech recognition scores for normal hearing children in environments with background noise levels above NC 30–35. NC curves present a method to derive a single number NC rating from the octave band or one-third octave band background noise spectrum in a classroom. Higher NC levels mean higher background noise levels in the room.

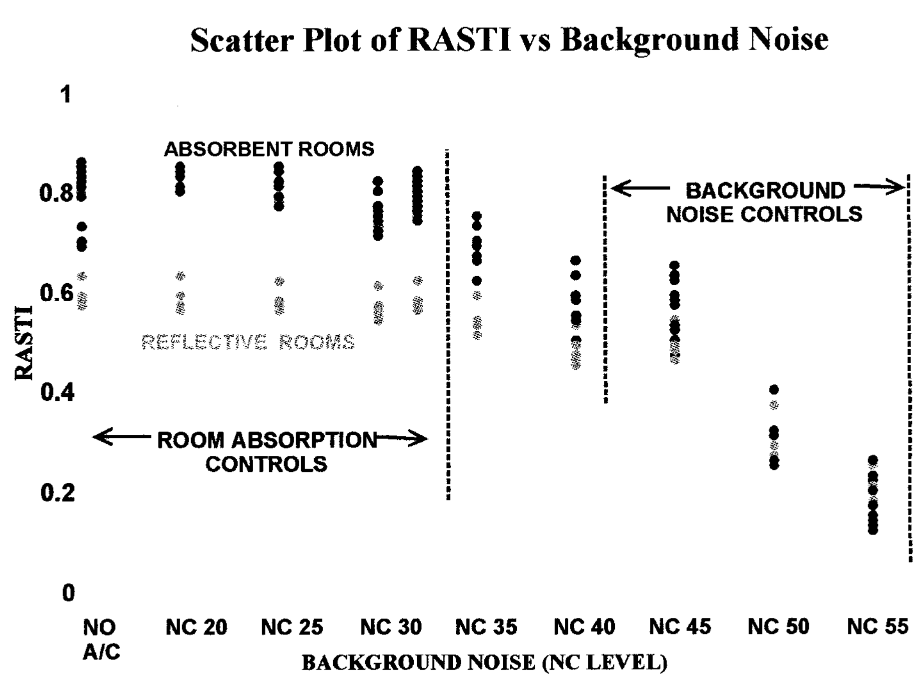
  A cause and effect relationship existed between system selection, system design, and noise in the rooms studied. Several general types of air-conditioning systems were found in the classrooms. These included (a) self-contained, wall-mounted air-conditioning units; (b) decentralized fan coil units and heat pumps with short duct runs; (c) central rooftop units serving multiple rooms; and (d) central systems with variable air volume controls. Rooms with the wall-mounted units and decentralized heat pumps with short duct runs had the highest NC levels. Rooms with central systems and sufficient duct lengths to attenuate sound had the lowest NC levels (Siebein, Gold, Ermann, & Walker, 1999; Siebein et al., 1997; Siebein et al., 1998).

  As shown in Figure 2, it is generally necessary to provide noise control devices in the air-conditioning system, such as silencers, adequate duct length, vibration isolators, and adequate duct and diffuser sizes, to achieve these sound levels. Specific design features for typical air handling units required to achieve sound levels of NC 30 in a room are listed in Tables 2 and 3.

- *Limit room volume (ceiling height).* Increased volume increases the reverberant tails of the impulse response or the "bad" reverberation in rooms. Ceiling heights that provide for a reasonable sense of space in the range of 9–12 feet will usually provide satisfactory results (Bradley, 1986; Knudsen & Harris, 1978). If the ceiling height is much higher than this, additional absorbent material will be necessary to control reverberation (Siebein et al., 1998).

- *Provide sound-absorbing surfaces.* The area of sound-absorbing materials should be approximately equal in area to the floor area of the room. For optimal

Figure 2. Background noise levels measured in a group of classrooms based on air-conditioning system type.



Note. RASTI = rapid speech transmission index.

Table 2. Noise control guidelines to reach noise criteria (NC) 30 levels in a room.

Design NC level for room	*Velocity in duct near terminal supply/return*	*Silencer length*	*Duct length to first inlet*	*Acoustical-lined flex duct required*
NC 30	400/500 fpm	3–7 ft	50–70 ft	6–8 ft

Note. fpm = feet per minute.

Table 3. Recommended maximum air velocities in feet per minute (fpm) for ducts based on noise criteria (NC) 30 level in a room.

	Free area of terminal	*First 10' of duct (from outlet)*	*Next 10' of duct*	*Next 10' of duct*	*Next 10' of duct*	*Next 10' of duct*
Supply	400	500	650	800	1050	1350
Return	500	600	750	950	1100	1550

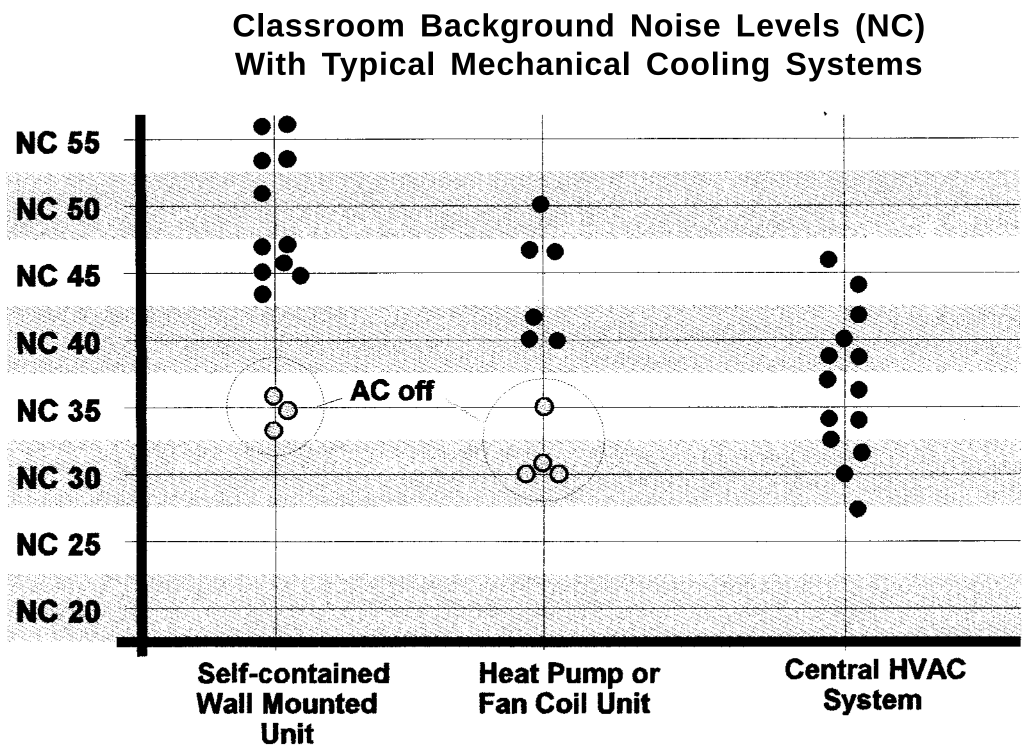
conditions, acoustical ceiling tile should be used on the side and rear portions of the ceilings of the rooms. Additional sound-absorbent panels should be located in a narrow band along the upper walls above the cabinets. If the room will be used for lecturing or teaching from a fixed position, gypsum board should be installed in one-third to one-half of the ceiling area above the teacher's location. This allows beneficial reflections from the ceiling to increase the apparent loudness of sounds for students toward the rear of the room (Knudsen & Harris, 1978; Reich & Bradley, 1998; Siebein et al., 1998).

Figure 3 shows that rooms with low background noise levels (NC < 35) and sound absorption materials have high RASTI values, providing excellent speech transmission. Sound-absorption materials that reduce reflections increase speech intelligibility significantly in these quiet rooms. On the other hand, rooms with high background noise levels (NC > 40) require more than just sound-absorption treatment. Both reflective and absorbent rooms have unacceptably low RASTI values. These noisy rooms require background noise controls as well as absorption control.

- *Install carpet on the floor.* Many teachers, who taught in both carpeted and vinyl tile rooms, commented that noise from fidgeting, especially in classrooms used for younger students, was reduced in carpeted rooms. Impact sounds, such as footsteps and moving chairs in multistory buildings, are also reduced with carpeted floors or with floors that have an acoustical underlayment between the floor and the vinyl tile (Egan, 1989). However, there are serious concerns for indoor air quality and potential allergenic effects from carpets in classrooms. Maintenance and replacement costs must be balanced with acoustical benefits. Additional studies covering these variables are needed to fully address this issue.
- *Emphasize classroom furniture arrangements and teaching techniques that reduce the distance between the teacher and the students.* The impact of alternative teaching strategies to traditional lecture-style teaching was assessed through a series of acoustical measurements. Alternate teaching strategies included small group instruction, rearranging of the desks to minimize teacher to student distances, story times at the front of the room, making use of the aisles, and general patterns of movement throughout the classroom by the teacher.

  In a typical lecture-style classroom, sound levels of the teacher's voice drop off by 6–9 dB from the front of the room to the back. This was accompanied by a decrease of more than 0.20 in STI as well. The alternate teaching methods described above that limited the distance between the teachers and the students resulted in less than a 4 dB decrease in sound level to the students. For example, when a teacher sat across a 6-foot diameter round table from a group of students for a reading session and the other students were seated around the room, the STI was 0.82 for a sound level decrease of 1 dB compared to an STI of 0.45 and a sound level decrease of 9 dB for students seated at the rear of the room. When the teachers held story time at the front, students in primary grades would sit on a carpeted floor within 10 feet of the teacher's chair from which she read. The sound level decreased by only 4 dB at the rear of this group. The same results were obtained when the teacher walked through the aisles during recitations in a foreign language class and arranged students in a circle in the center of the room, and for an English class discussing literature in a middle school. The acoustical impact of these simple teaching techniques is significant enough that teachers should be made aware of these findings and instructed on how to

Figure 3. Relationship between the rapid speech transmission index (RASTI) and background noise levels found in the computer model studies.



implement them in the classroom (Hasell et al., 1998; Siebein et al., 1997).

Nontraditional seating arrangements also reduce the distance of student to teacher. Desks can be arranged in a "Y" arrangement, a conference arrangement, or in small groups to reduce the decrease in sound level that occurs in a typical row and aisle seating arrangement. Class sizes should be reduced to approximately 25–30 students, who then should be arranged in the classroom so none are more than 12 feet from the teacher. As the teacher walks through the room, these distances are further reduced. A rectangular floor plan rather than a square plan offers a potentially interesting way to minimize teacher-to-student distances (Siebein et al., 1998).

- *Use FM and other sound reinforcement systems when needed.* For some children, sufficient sound level cannot be achieved using traditional quieting and sound-absorbing materials. For those circumstances, amplification systems are needed. There is a substantial body of work that reports the advantages of amplification systems used in classrooms. These systems consist of a wireless microphone used by the teacher to pick up his or her voice. The teacher's voice is then amplified and played through loudspeakers that are carefully located in the classroom to increase the loudness of speech sounds for children in the room (Crandell et al., 1995; Smaldino & Crandell, this issue).
- S*elect and design the overall site plan wisely.* Sites for schools should be isolated from major transportation and industrial noise sources. If sites that are near major highways, airports, rail lines, or other sources of noise must be chosen, appropriate mitigation measures should be incorporated in the envelope of the building (Finitzo-Heiber & Tillman, 1978).

  Furthermore, the site should be carefully planned to avoid acoustical "hot spots." This includes locating special purpose rooms, such as computer and music rooms, so that students do not have to walk past every classroom in the building to get to them. Loud activities such as physical education fields, music rooms, and so forth, should be located so that sounds from these areas do not disturb children in regular classrooms.

  Site planning also includes selecting reasonable sound transmission class (STC) ratings for walls, doors, and windows to limit the transmission of sound between and among rooms. The STC is a single number weighted average of the amount of sound energy in decibels that is "lost" or reduced as it travels through a wall, roof, floor, window, or door (Egan, 1989). Sound isolation between classrooms is an increasing concern as multimedia amplified sounds of various types are introduced as a normal part of classroom activities.

- *Design special-purpose rooms with special-purpose acoustics*. Rooms such as gymnasiums, cafeterias, theaters, music rooms, shops, and vocational/technical areas should be designed with special-purpose acoustics. Overall noise reduction is essential for reasonable acoustical conditions in gymnasiums, cafeterias, and shops. Usually, inadequate wall surface area is available, which limits the amount of absorbing materials that can be located to reduce noise to ideal levels.

  The primary design goal is to reduce noise to as reasonable a level as possible using sound-absorbing materials with as high an NRC as practical on the ceiling and covering exposed wall areas above head height with absorbing materials that are resistant to damage. In auditoria, theaters, music rooms, and drama classrooms, sound projection and diffusion become important considerations for the teaching of performing arts, even more so than just RT; therefore, angled or splayed walls, diffusing panels on the walls and ceilings, and acoustical shaping become important principles in addition to the control of reverberation (Egan, 1989; Knudsen & Harris, 1978).
- *Work with audiologists, teachers, and acoustical consultants who have expertise in the design and planning of classrooms*. The acoustical analysis and design of HVAC systems, room acoustics, and FM sound systems are the domain of experienced professionals. The assessment of the communication skills of young children in complex environments, such as classrooms, requires the special attention of professionals as well. The two major professional groups for acoustical consultants in the United States are listed in the Appendix.
- *Support a vigorous national technical research effort in this area to fully explore these issues relating to speech perception and learning for all children.* An adequate body of knowledge or database has not been developed that can link newer measures of room acoustical qualities with students' perception, listening, learning, and communication skills. This is especially true for younger students and for those students with a variety of moderate-to-severe hearing impairments (Bradley, 1986; Crandell et al., 1995; Hodgson, 1999).

CONCLUSIONS

The 10 factors discussed determine to a large extent the architectural factors that affect the acoustical learning environment of classrooms. Successful classrooms for all students require a holistic planning, design, and construction process that considers not only the physical size and layout of the rooms, but also other factors. These include the air-conditioning system design and selection, construction materials and assemblies, site selection and design, and the use of room amplification systems in concert with the specific teaching methods used by teachers in the classroom.

It is necessary to include an audiologist and an acoustical consultant on the design team for new and remodeled facilities to accomplish a satisfactory learning environment. This is necessary for two reasons. First, professional analysis and design services should be provided. Second, a person on the design team should serve as an advocate for maintaining suitable acoustical qualities in classrooms during the value engineering process that allows schools to be constructed under very tight budget restraints. (Value engineering is the effort to find more economical methods to achieve identical levels of performance in a building.) Cost is often the primary indicator of performance that is considered in many value engineering processes. A new body of knowledge must be developed relating to acoustical performance that can be used in the value engineering process. This research should address the real issues that currently prevent classrooms from providing the high-quality acoustical environments students deserve. The research should be based on further studies of impulse response acoustical measurements and how these measures specifically relate to the unique perceptual, speech, communication, and learning abilities of young children.

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APPENDIX. PROFESSIONAL ASSOCIATIONS OF ACOUSTICAL CONSULTANTS IN THE UNITED STATES

National Council of Acoustical Consultants
66 Morris Ave., Suite 1A
Springfield, NJ 07081-1409
(973)564-5859 (voice)
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email: pallen@1-2000.com
web site: www.ncac.com

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(914)462-0201 (fax)
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