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Clinical Forum

Classroom Acoustics for Children With Normal Hearing and With Hearing Impairment

Carl C. Crandell
University of Florida, Gainesville
Joseph J. Smaldino
University of Northern Iowa, Cedar Falls

The accurate transmission of acoustical information in a classroom is imperative for optimal academic achievement. Unfortunately, speech perception ability in a classroom setting can often be deleteriously affected by the acoustical characteristics of that environment. Acoustical variables that can compromise perceptual abilities include the reverberation time (RT) of the enclosure, the overall level of the background noise, the relationship between the level of the teacher's voice and the background noise, and the distance from the teacher to the child.

ABSTRACT: Past investigations demonstrate that the acoustical environment of a classroom is a critical factor in the academic, psychoeducational, and psychosocial achievement of children with normal hearing and with hearing impairment. This article examines several acoustical variables, such as noise, reverberation, and speaker-listener distance, which can deleteriously affect speech perception in classrooms. Moreover, the discussion examines the effects of these variables on the speech perception abilities of both children with normal hearing and children with hearing loss. Finally, appropriate acoustical criteria are suggested for children in educational settings.

KEY WORDS: noise, reverberation, speaker-listener distance, speech perception, psychoeducational/psychosocial achievement

In addition to the acoustical environment, speech perception in a classroom can also be decreased by reductions in the hearing sensitivity or auditory processing abilities of the child. In fact, it is well recognized that the major sequelae of sensorineural hearing loss (SNHL) are speech perception difficulties, particularly in noisy or reverberant listening environments. (For a review of past investigations, see Crandell, 1991; Crandell & Smaldino, 2000a, 2000b; Crandell, Smaldino, & Flexer, 1995.) With these considerations in mind, the present discussion will address (a) the acoustical variables that can influence speech perception in classrooms (noise, reverberation, and distance) and (b) the effects of these acoustical variables on the speech perception of children with SNHL and children with normal hearing. Moreover, this discussion will suggest appropriate noise and reverberation levels for such populations of children.

ACOUSTICAL VARIABLES IN CLASSROOMS

To understand why children experience speech perception difficulties in the classroom, it is important that disciplines working in the educational setting (such as audiologists, speech-language pathologists, reading specialists, regular and special education teachers, teachers of the deaf and hearing impaired, and psychologists) have an adequate knowledge base concerning the acoustical

0161–1461/00/3104–0362

variables that can compromise the perception of speech. As noted in the introduction, these acoustical variables include the (a) level of the background noise, (b) level of the speech signal relative to the level of the background noise, (c) RT, and (d) distance from the speaker to the listener. Each of these variables is discussed in subsequent sections.

Background Noise

In classrooms, speech is infrequently transmitted to a child without interference from background noise. Background noise refers to any undesired auditory stimuli that interferes with what a child wants, or needs, to hear and understand (Crandell et al., 1995). Background noise sources in the classroom include external noise (noise that is generated from outside of the building, such as airplane traffic, local construction, automobile traffic, and playgrounds), internal noise (noise that originates from within the building, but outside of the classroom, such as rooms adjacent to cafeterias, lecture rooms, gymnasiums, and/or busy hallways), and room noise (noise that is generated within the classroom) (Bess & McConnell, 1981; Crandell & Smaldino, 1994, 1995, 1996, 2000b; Olsen, 1981, 1988). Sources of room noise include individuals talking, sliding of chairs or tables, and shuffling of hard-soled shoes on non-carpeted floors. Heating, ventilating, and air-conditioning (HVAC) systems usually also significantly contribute to classroom noise levels. Due to the myriad of potential sources of noise, classrooms often exhibit excessive levels of background noise. Table 1 presents a summary of five studies that have measured background noise levels in classrooms.

It should be noted, however, that background noise in a classroom often varies considerably as a function of time. This variability often makes it difficult to measure classroom noise reliably in a simple manner. In spite of this difficulty, most studies of classroom noise report background noise levels via single number descriptions (Crandell et al., 1995). The most common single number descriptor of classroom noise is the measurement of the relative sound pressure level (SPL) of the background noise at a specific point, or points, in time on an A-weighting scale (dBA). Such measures are usually conducted with a sound level meter. The A-weighting network is designed to simulate the sensitivity of the average human ear under conditions of low sound loudness (40 phons). Unfortunately, the single number obtained from a sound pressure measurement performed with the A-weighting can be obtained with a number of very different spectra.

A more thorough procedure to measure background noise in a classroom is via the use of noise criteria (NC) curves (Beranek, 1954). NC curves are a family of frequency/intensity curves based on octave-band sound pressure across a 20–10,000 Hz band that have been related to successful use of an acoustical space for a variety of activities. With NC curves, a spectral analysis of the noise (usually from 63 Hz to 8000 Hz) in octave bands, or one-third octave bands, is conducted. These data are then plotted across eight standard frequencies. The NC value that characterizes a room is determined by the highest octave band sound pressure level that intersects the NC family of curves. The NC rating is generally 8–10 dB below the dBA level of that room.

To illustrate the advantages of this procedure over a single number descriptor, assume that there was a great deal of low-frequency noise present in an enclosure. This noise would have a great effect on the NC unit assigned to the room; however, a single number measure, such as dBA, would not provide enough detail to identify and reduce specific frequency bands of noise. It is recommended, therefore, that whenever noise is interfering with communication, background noise levels in rooms be measured via NC measures because this procedure gives the examiner additional information regarding the spectral

Table 1. Summary of studies that have examined unoccupied and occupied classroom background noise levels.

	Classroom noise levels	
Study	*Unoccupied levels*	*Occupied levels*
Sanders (1965)	42 dBB to 58 dBB	52 dBB to 69 dBB
Nober & Nober (1975)	DNR	65 dBA
Bess, Sinclair, & Riggs (1984)	41 dBA, 50 dBB, 58 dBC	56 dBA, 60 dBB, 63 dBC
Finitzo-Hieber (1988)	DNR	48 dBA to 68 dBA
Crandell & Smaldino (1995)	51 dBA, 67 dBC	DNR

Note. DNR = Investigation did not report these data. The A-weighting network is designed to simulate the sensitivity of the average human ear under conditions of low sound loudness (40 phons). The B-weighting simulates loud sound (70 phons); the C-weighting approximates how the ear would respond to very loud sound.

characteristics of the noise. Specifically, with this information, the audiologist or acoustical engineer can isolate and modify sources of excessive noise in the room.[1]

Background noise in a classroom affects the child's ability to perceive speech by masking the acoustic and linguistic cues that are available in the teacher's spoken message. In general, the spectral energy of consonants is less intense than vowel energy. Consequently, background noise in the classroom predominately reduces consonant perception. Unfortunately, even minimal decreases in consonant perception can significantly influence speech perception because the vast majority of a listener's ability to understand speech is the result of consonantal energy (French & Steinberg, 1947; Licklider & Miller, 1951). The capability of classroom noise to mask the teacher's speech depends on a number of acoustical parameters (Nabelek, 1982; Nabelek & Nabelek, 1994). These parameters include (a) the long-term spectrum of the noise, (b) intensity fluctuations of the noise over time, and (c) the intensity of the noise relative to the intensity of speech.

The most effective maskers for speech are usually those noises with a long-term spectra that are similar to the speech spectrum because they affect all of the speech frequencies to the same degree. Consequently, noises generated within the classroom (such as children talking) often produce the greatest decreases in speech perception because the spectral content of the signal (the teacher's voice) is spectrally similar to the spectra of the noise. Low-frequency noises in a classroom (such as air-conditioning units) are usually more effective maskers of speech than high-frequency sounds because of the upward spread of masking. Due to the upward spread of masking, noise tends to produce greater masking for signals that are higher in frequency than the noise. Classroom noises that are continuous in nature are generally more effective maskers than interrupted or impulse noises. These differences in masking occur because continuous noises more effectively reduce the spectral-temporal information available in the speech signal. Continuous noises in the classroom include the hum of air conditioning or heating systems, faulty fluorescent lighting, and the long-term spectra of children talking.

Signal-to-Noise Ratios (SNRs) in Classrooms

In most learning environments, the most important consideration for accurate speech perception is not the type of noise or overall background noise level, but, rather, the relationship between the intensity of the signal and the intensity of the background noise at the child's ear. This relationship is often referred to as the signal-to-noise ratio (SNR). To illustrate, if a speech signal is presented at 75 dB, and a noise is 65 dB, the SNR would be +10 dB. Generally speaking, speech perception ability is highest at favorable SNRs and decreases as a function of reduction in SNR (Crum, 1974; Finitzo-Hieber & Tillman, 1978; Nabelek & Pickett, 1974a, 1974b). Due to the excessive noise levels found in many learning environments, it should not be surprising that unfavorable SNRs have often been reported in classrooms. Specifically, as can be noted from Table 2, the range of SNRs for classrooms has been reported to be from approximately +5 dB to -7 dB. The effects of poor SNRs on the perceptual abilities of children in classroom settings will be addressed later.

Noise Effects on Academic and Teacher Performance

In addition to deleteriously affecting speech recognition, background noise can also compromise academic performance, reading and spelling skills, concentration, attention, and behavior in children (Ando & Nakane, 1975; Crook & Langdon, 1974; Dixon, 1976; Green, Pasternak, & Shore, 1982; Ko, 1979; Koszarny, 1978; Lehman & Gratiot, 1983; Sargent, Gidman, Humphreys, & Utley, 1980). Koszarny (1978) reported that noise levels tend to affect concentration and attention more seriously in children with lower IQs or high anxiety levels. Green et al. (1982) reported that background noise levels in classrooms were significantly related to reading scores in elementary school-age children. Specifically, the higher the background noise level of the classroom, the poorer the reading scores exhibited by students in that classroom. Lehman and Gratiot (1983) reported that reductions in classroom noise (via acoustical modification) had a significant effect on increasing concentration, attention, and participatory behavior in children. Interestingly, noise levels were reduced from typically reported noise levels of 35–45 dBA to the suggested guideline of 30 dBA.

Classroom noise has also been shown to affect teacher performance (Crook & Langdon, 1974; Ko, 1979; Sargent et al, 1980). For example, Ko (1979) obtained information from more than 1,200 teachers concerning the effects of noise in the classroom. Results indicated that noise related to classroom activities and traffic or airplane noise were correlated with teacher fatigue, increased tension and discomfort, and an interference with teaching and speech

Table 2. A summary of studies examining classroom signal-to-noise ratios.

Study	*Signal-to-noise ratio*
Sanders (1965)	+1 to +5
Paul (1967)	+3
Blair (1977)	-7 to 0
Markides (1986)	+3
Finitzo-Hieber (1988)	+1 to +4

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[1] A similar concept to NC curves is room criteria (RC) curves. In the development of RC curves, NC curves were modified to include higher and lower frequencies that are commonly associated with mechanical noises (heating or air-conditioning units).

recognition. Additional studies (Crandell et al, 1995; Sapienza, Crandell, & Curtis, 1999) reported that teachers exhibit a significantly higher incidence of vocal problems than do the general population. It is reasonable to assume that these vocal difficulties are caused, at least in part, by having to increase vocal output to overcome the effects of classroom noise during the school day.

Reverberation Time

An additional acoustical variable that can detrimentally affect speech perception in the classroom is reverberation. Reverberation refers to the persistence or prolongation of sound within an enclosure as sound waves reflect off of hard surfaces (Lochner & Burger, 1964; Nabelek & Pickett, 1974a, 1974b; Siebein, 1994; Siebein, Crandell, & Gold, 1997). This prolongation of sound is usually considered the most important acoustical consideration that defines the acoustical climate of a classroom. RT is defined as the time (in seconds) it takes for the sound from a source to decrease in level by 60 dB after the source has stopped. A decrease of 60 dB represents a reduction of 1/1,000,000 of the original intensity of the sound. A common formula to calculate RT was described by Sabine (1964):

$$RT_{60} = \frac{0.049V}{\Sigma S\alpha}$$

where RT_{60} = RT in seconds, 0.049 is a constant (use 0.161 if room volume is stated in meters), V = room volume in cubic feet, and $\Sigma S\alpha$ = the sum of the surface areas of the various materials in the room multiplied by their respective absorption coefficients at a given frequency. If one reviews the variables in the RT formula described above, it can be seen that there are two basic factors that affect the RT in a room. The first is the room volume. The larger the room volume, the longer the RT will be. The second variable is the amount of sound absorption in the room. The greater the area of such materials, the shorter the RT.

RT is often reported as the mean decay time at 500, 1000, and 2000 Hz. This average describes the characteristics of most rooms fairly well. Unfortunately, such a measurement paradigm may not adequately describe the reverberant characteristics of a room because high RTs may exist at additional frequencies. Room reverberation varies as a function of frequency and, therefore, may need to be measured at discrete frequencies. Generally, because most materials do not absorb low frequencies well, room reverberation is shorter at higher frequencies and longer in lower frequency regions. It is recommended that RT be measured at discrete frequencies from 125 to 8000 Hz, whenever excessive reverberation seems to interfere with communication. Such information could significantly aid the audiologist in determining the appropriate degree and type of absorptive materials needed for a reduction of RT in that environment.

Reverberation can affect speech perception through the masking of direct and early-reflected energy by reverberant energy (Bolt & MacDonald, 1949; Lochner & Burger, 1964; Nabelek, 1982; Nabelek & Pickett, 1974a, 1974b). To explain, the reverberant speech energy reaches the listener after the direct sound, and overlaps with that direct signal, resulting in a “smearing” or masking of speech. Like noise, reverberation tends to affect consonant perception adversely. Specifically, reverberation causes a prolongation of the spectral energy of the vowel sounds, which masks succeeding consonant phonemes, particularly those consonants in word final positions. The masking effect of reverberation is more noticeable for vowels than for consonants because vowels exhibit greater overall power and are of longer duration than consonants. In highly reverberant environments, words may actually overlap with one another, thus causing reverberant sound energy to fill in temporal pauses between words and sentences. RTs of classrooms generally have been reported to be higher than desired for optimum communication to occur. Specifically, as can be noted from Table 3, the range of reverberation for classroom settings is typically reported to be from 0.4 to 1.2 seconds.

Combined effects of noise and reverberation. In the classroom setting, noise and reverberation combine synergistically to affect speech perception (Crandell & Bess, 1986; Crum, 1974; Finitzo-Hieber & Tillman, 1978; Nabelek & Pickett, 1974a, 1974b). That is, the interaction of noise and reverberation adversely affects speech perception to a greater extent than the sum of both effects taken independently. To illustrate, if an individual is listening to speech in a quiet room, the addition of a specific noise (e.g., the starting of an air conditioner) might reduce that listener’s perception by 10%. In another quiet room, the presence of some reflective surfaces, and thus reverberation, might reduce perpetual abilities, also by 10%. However, if both noise and reverberation were present in a room, their combined effects on speech perception might actually equate to a 40% to 50% reduction in speech perception (Crandell et al., 1995). These synergistic effects appear to occur because when noise and reverberation are combined, reflections fill in the temporal gaps in the noise, making it more steady state in nature.

Table 3. A summary of five studies examining classroom reverberation times.

Study	*Reverberation time in seconds*
Kodaras (1960)	0.40 to 1.10
Nabelek & Pickett (1974a)	0.50 to 1.00
McCroskey & Devens (1975)	0.60 to 1.00
Bradley (1986)	0.39 to 1.20
Crandell & Smaldino (1994)	0.35 to 1.20

Speaker-to-Listener Distance

A final factor that influences speech perception in the classroom is the distance from the teacher to the student. At distances relatively close to the child, the direct sound field predominates in the listening environment. In this sound field, sound waves are transmitted from the teacher to the child with minimal interference from room surfaces.

Direct sound pressure follows the principle of the inverse square law, which states that sound level decreases 6 dB for every doubling of distance from the sound source. As the child moves away from the teacher, the indirect or reverberant field begins to dominate the listening environment. The indirect sound field originates at the "critical distance" of the room. The critical distance of the room refers to the point in the room where the level of the direct sound and the level of the reverberant sound are essentially equal. Operationally, critical distance (D_c) is defined by the following formula:

$$D_c = 0.20\sqrt{VQ/nRT}$$

where V = volume of the room in m^3, Q = directivity factor of the source (the human voice is approximately 2.5), n = number of sources, and RT = reverberation time of the enclosure at 1400 Hz. In an average-sized classroom, with a commonly reported level of reverberation, the critical distance of the room would be approximately 3–4 meters from the teacher.

Beyond the critical distance, the direct sound from the speaker arrives at the listener initially, but is followed by reverberated signals that are composed of the original wave that has now been reflected off of the ceiling, walls, and floor. Because there is a linear decrease in the intensity of the direct sound, and because the absorptive characteristics of structures in the room absorb some frequencies more than others, the reflected sound reaching the listener will contain a different acoustical content in the intensity, frequency, and temporal domains.

The distance a child is from the teacher can strongly influence speech perception. Specifically, when the child is within the critical distance (the direct sound field), reverberation will have minimal effects on speech perception. Beyond the critical distance (the indirect sound field), however, these reflections can significantly reduce speech perception, particularly if there is a sufficient spectral or intensity change in the reflected sound to interfere with the perception of the direct sound. Speech perception scores decrease until the critical distance of the room is reached (Crandell, 1991; Crandell & Bess, 1986; Leavitt & Flexer, 1991; Peutz, 1971). Beyond the critical distance, perception ability tends to remain essentially constant in the classroom. This finding suggests two implications. First, speech perception ability can only be improved by decreasing the distance between a speaker and listener within the critical distance of the room. Second, the recommendation for preferential seating has significant limitations. In typical classrooms, the critical distance for maximum speech perception is present only at distances that are relatively close to the teacher. Hence, the simple recommendation of preferential seating is often not enough to ensure an appropriate listening environment for many children.

SPEECH PERCEPTION IN THE CLASSROOM

Children with SNHL

Now that the reader understands the acoustical variables that can affect speech perception in a classroom, the effects of these variables on various populations of children will be addressed. As previously noted, it is well recognized that the most common complaint of listeners with SNHL is difficulty understanding speech, particularly in noisy listening environments. Specifically, although speech perception in adult listeners with normal hearing is not significantly affected until the SNR is approximately 0 dB, listeners with SNHL require the SNR to be improved by 4–12 dB, and by an additional 3–6 dB in rooms with moderate levels of reverberation in order to obtain perception scores that are equal to those of normal hearers (see Crandell & Smaldino, 2000a, 2000b for a review of these investigations). It is also well documented that listeners with SNHL require shorter RTs than normal hearers for optimal communication. Speech perception in adults with normal hearing is not compromised until the RT exceeds approximately 1.0 second (Crandell et al., 1995; Crum, 1974; Nabelek & Pickett, 1974a, 1974b). Listeners with SNHL, however, report significant perceptual difficulties when the RT exceeds approximately 0.4 second (Crandell, 1991, 1992, 1993; Crandell & Bess, 1986; Crandell et al., 1995; Finitzo-Hieber, 1988; Finitzo-Hieber & Tillman, 1978; Neimoeller, 1968; Olsen, 1981, 1988).

An illustration of the effects of hearing impairment on speech perception in the classroom is presented in Table 4. These data, taken from a seminal investigation by Finitzo-Hieber and Tillman (1978), show the speech perception abilities of children (8–12 years of age) with mild-to-moderate degrees of SNHL compared to children with normal hearing sensitivity. Speech perception was assessed with monosyllabic words under various SNRs (SNRs = quiet, +12, +6, 0) and RTs (RT = 0.0, 0.4, and 1.2 seconds). Results from this investigation reveal several trends.

- These data indicate that the children with hearing impairment performed significantly poorer than did the children with normal hearing across most listening conditions.
- The performance decrement between the two groups increased as the listening environment became less favorable. For example, in what would be an extremely good classroom environment (SNR = +12 dB; RT = 0.4 second), children with hearing impairment obtained perception scores of only 60% as compared to 83% for the normal hearers. In acoustical conditions more commonly reported in the classroom (SNR = +6 dB; RT = 1.2 seconds), children with SNHL obtained perception scores of just 11% as compared to 27% for children with normal hearing.

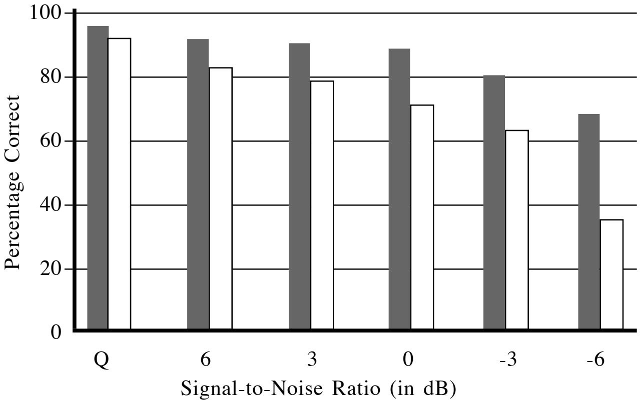
Table 4. Mean speech recognition scores (in % correct) by children with normal hearing (n = 12) and children with sensorineural hearing loss (n = 12) for monosyllabic words across various signal-to-noise ratios and reverberation times (RTs). Table adapted from Finitzo-Hieber & Tillman (1978).

	Groups	
Testing condition	*Normal hearing*	*Hearing impaired*
RT = 0.0 second		
Quiet	94.5	83.0
+12 dB	89.2	70.0
+ 6 dB	79.7	59.5
0 dB	60.2	39.0
RT = 0.4 second		
Quiet	92.5	74.0
+12 dB	82.8	60.2
+ 6 dB	71.3	52.2
0 dB	47.7	27.8
RT = 1.2 Seconds		
Quiet	76.5	45.0
+12 dB	68.8	41.2
+ 6 dB	54.2	27.0
0 dB	29.7	11.2

- Although not shown in this table, it is interesting to note that the addition of a hearing aid did not improve perceptual ability and, in fact, made understanding even more difficult in many listening conditions. Certainly, it is reasonable to assume that learning and academic achievement will be significantly compromised with such poor perceptual scores.

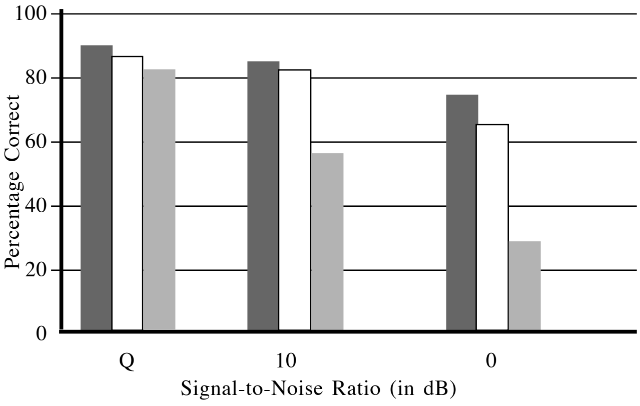
Additional investigations have demonstrated that poor classroom acoustics can also compromise the perceptual abilities of children with minimal or unilateral degrees of SNHL (see Bess, 1985 and Crandell et al., 1995 for a review of these investigations). Crandell (1993), for example, examined the speech perception of children with minimal degrees of SNHL at commonly reported classroom SNRs of +6, +3, 0, -3, and -6 dB. Children with minimal SNHL exhibited pure tone averages (0.5 kHz to 2 kHz) from 15 to 25 dB HL. Speech perception was assessed with sentential materials. Multitalker babble was used as the noise competition. Mean sentence perception scores (in percentage correct) as a function of SNR are presented in Figure 1. Trends from these data are similar to those reported in children with greater degrees of SNHL. That is, children with minimal degrees of hearing impairment performed more poorly than normal hearers across most listening conditions. Moreover, note that the differences in perception scores between the two groups increased as the listening environment became more adverse. For example, at an SNR of +6 dB, both groups obtained perception scores in excess of 80%. At an SNR ratio of -6 dB, however, the group that had minimal hearing impairments was able to obtain less than 50% correct perception compared to approximately 75% perception ability for the normal hearers.

Figure 1. Mean speech recognition scores (in % correct) of children with normal hearing (shaded bars) and children with minimal degrees of sensorineural hearing loss (clear bars) in quiet and at various signal-to-noise ratios. Figure adapted from Crandell, Smaldino, & Flexer (1995).



Bess, Tharpe, and Gibler (1986) examined speech perception in 25 children with mild-to-severe degrees of unilateral SNHL. Speech perception was assessed with consonant-vowel (CV) or vowel-consonant (VC) syllables from the Nonsense Syllable Test (NST, Levitt & Resnick, 1978) at several SNRs (SNR = quiet, +20, +10, 0, and -10 dB). The speech stimuli were presented to the children in two common classroom listening conditions: (a) monaural direct (speech directed at the good ear, noise presented to the bad ear) and (b) monaural indirect (noise presented to the good ear, speech presented to the same ear). Data from this investigation are shown in Figure 2. Although the children with unilateral hearing impairment performed similarly to the normal hearers in quiet, significant differ-

Figure 2. Mean speech recognition scores (in % correct) of children with normal hearing (dark bars), children with unilateral sensorineural hearing loss in a monaural direct listening condition (clear bars), and children with unilateral sensorineural hearing loss in a monaural indirect listening condition (light bars) at various signal-to-noise ratios. Figure adapted from Bess, Tharpe, & Gibler (1986).



ences in perceptual ability were noted between the groups in the noisy listening conditions, particularly in the monaural indirect condition.

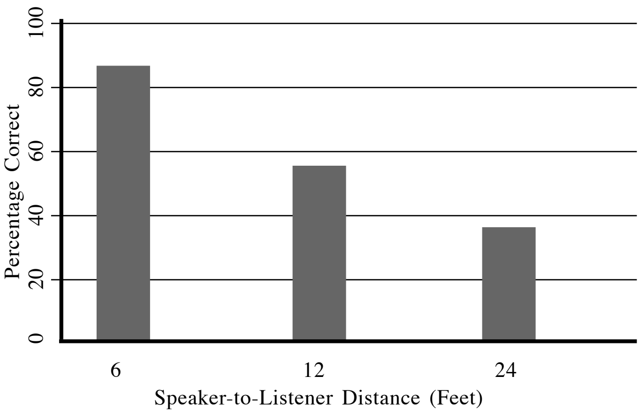
Children with Normal Hearing

In addition to listeners with SNHL, there are populations of children with normal hearing sensitivity who exhibit greater perceptual difficulties in noise and reverberation than traditionally has been suspected (Bess, 1985; Bess & Tharpe, 1986; Boney & Bess, 1984; Crandell, 1991, 1992, 1993; Crandell & Flannagan, 1999; Crandell & Smaldino, 1992, 1994, 1996, 2000b; Crandell et al., 1995; Nabelek & Nabelek, 1994). The largest population of children who are at risk for noise interference are pediatric listeners younger than 15 years of age. It should not be surprising that younger children have greater perceptual difficulties than adults.

A number of investigators have demonstrated that children with normal hearing sensitivity require higher SNRs and lower RTs than adult normal hearers to achieve equivalent perception scores (Crandell, 1992, 1993; Crandell & Smaldino, 1992, 1994, 1995, 1996, 2000a; Crandell et al., 1995; Elliott, 1979, 1982; Elliott et al., 1979; Nabelek & Nabelek, 1994). Adult-like performance on perception tasks in noise or reverberation is generally not reached until the child reaches approximately 13–15 years of age. Based on these data, it is reasonable to hypothesize that commonly reported levels of classroom noise and reverberation can deleteriously affect the speech perception of younger children with normal hearing sensitivity. To support this assumption, the reader is once again directed to Table 4, which shows data by Finitzo-Hieber and Tillman (1978). Although these investigators focused on the perceptual abilities of children with SNHL, Table 4 also presents the speech perception data for children with normal hearing. Note that in typical classroom listening environments, children with normal hearing generally obtained poor perception scores. For example, in a relatively good classroom listening environment (SNR = +6 dB; RT = 0.4 second), these children were able to recognize 71% of the stimuli. In a poor, but commonly reported classroom environment (SNR = 0 dB; RT = 1.2 seconds), perception scores were reduced to less than 30%.

In another study that investigated the perceptual abilities of children in "typical" classrooms, Crandell and Bess (1986) examined the speech perception of young children (5–7 years old) with normal hearing in a classroom environment (SNR = +6 dB; RT = 0.45 second). Monosyllabic words were presented to the children at speaker-to-listener distances (SLDs) of 6, 12, and 24 feet. Results from this investigation are presented in Figure 3. As can be noted, there was a systematic reduction in speech perception ability as SLD increased. Specifically, mean perception scores of 89%, 55%, and 36% were obtained at 6, 12, and 24 feet, respectively. Overall, these data, and those of Finitzo-Hieber and Tillman (1978), suggest that children seated in a typical classroom setting have greater difficulty understanding speech than has traditionally been suspected.

Figure 3. Mean speech recognition scores (in % correct) of children with normal hearing in a "typical" classroom environment (signal-to-noise ratio = +6 dB, RT = 0.6 seconds) as a function of speaker-to-listener distance. Figure adapted from Crandell and Bess (1986).



SUGGESTED ACOUSTICAL GUIDELINES

Although a number of acoustical, linguistic, and articulatory factors influence the determination of appropriate acoustical conditions in a room, prior literature suggests that SNRs in communication environments for listeners with SNHL should equal or exceed +15 dB, unoccupied background noise levels should not surpass 30–35 dBA, and RTs should not be higher than 0.4–0.6 second (American Speech-Language-Hearing Association [ASHA], 1995; Bess & McConnell, 1981; Crandell & Smaldino, 1994, 1995, 1996, 2000a, 2000b; Crandell et al., 1995; Finitzo-Hieber, 1988; Finitzo-Hieber & Tillman, 1978; Flexer, 1992; Fourcin et al., 1980; Gengel, 1971; Olsen, 1981, 1988). These recommendations are based on the findings that the speech perception of listeners with hearing impairment tend to remain relatively constant at SNRs in excess of +15 dB (or RTs lower than 0.6 second), but deteriorate at poorer SNRs (or higher RTs). Moreover, it has been demonstrated that, when these acoustical criteria are not obtained, persons with hearing loss have to expend so much attentional effort in listening to the message that they often prefer to communicate through other modalities. Acoustical guidelines have also not been developed for children with normal hearing who are at risk for noise interference (such as younger children). Until such standards are clarified, it has been recommended that SNRs and RTs in learning environments should follow those recommended for children with SNHL (ASHA, 1995; Crandell & Smaldino, 1996, 2000b; Crandell et al., 1995)

A review of the literature suggests that these acoustical recommendations are rarely achieved in everyday learning environments (Berg, 1993; Bess, Sinclair, & Riggs, 1984; Crandell, 1991; Crandell & Smaldino, 1995, 2000b; Crum & Matkin, 1976; McCroskey & Devens, 1975). Crandell and Smaldino (1995), for example, reported that only 9 of

32 classrooms (27%) studied showed RTs of 0.4 second or less. No classroom met the recommended criteria for noise. Fortunately, federal standards that regulate room noise levels and reverberation for children with SNHL and “normal hearing” are currently in development. This federal standard is described in greater detail in other articles within this clinical forum.

CONCLUSIONS

The preceding discussion has addressed several of the important acoustical variables (noise, reverberation, and distance) that are present in a classroom. Moreover, this discussion has shown that commonly reported classroom acoustics can have an adverse effect on the speech perception of children with SNHL and normal hearing sensitivity. Such findings are alarming because inappropriate classroom acoustics can deleteriously affect not only speech perception, but also psychoeducational and psychosocial achievement. The speech perception deficits experienced by these children highlight the need to strongly consider the acoustical conditions in listening environments used by such populations.

Unfortunately, at this time, federal standards do not currently exist for classroom acoustics. Considerable speech perception data suggest that for maximum communication to occur in such populations, SNRs should exceed +15 dB, unoccupied noise levels should not exceed 30–35 dBA, and reverberation levels should not surpass 0.4–0.6 second.

REFERENCES

American Speech-Language-Hearing Association. (1995). Guidelines for acoustics in educational environments. *Asha, 37* (Suppl. 14), 15–19.

Ando, Y., & Nakane, Y. (1975). Effects of aircraft noise on the mental work of pupils. *Journal of Sound and Vibration, 43,* 683–691.

Beranek, L. (1954). *Acoustics*. New York: McGraw-Hill.

Berg, F. (1993). *Acoustics and sound systems in schools*. Boston, MA: College-Hill Press.

Bess, F. (1985). The minimally hearing-impaired child. *Ear and Hearing, 6*, 43–47.

Bess, F., & McConnell, F. (1981). *Audiology, education and the hearing-impaired child*. St. Louis, MO: C.V. Mosby.

Bess, F., Sinclair, J., & Riggs, D. (1984). Group amplification in schools for the hearing-impaired. *Ear and Hearing, 5*, 138–144.

Bess, F., & Tharpe, A. (1986). An introduction to unilateral sensorineural hearing loss in children. *Ear and Hearing*, *7*, 3–13.

Bess, F., Tharpe, A., & Gibler, A. (1986). Auditory performance of children with unilateral sensorineural hearing loss. *Ear and Hearing, 7*, 20–26.

Blair, J. (1977). Effects of amplification, speechreading, and classroom environment on reception of speech. *Volta Review, 79*, 443–449.

Bolt, R., & MacDonald, A. (1949). Theory of speech masking by reverberation. *Journal of the Acoustical Society of America, 21*, 577–580.

Boney, S., & Bess, F. (1984, October). *Noise and reverberation effects in minimal bilateral sensorineural hearing loss*. Paper presented at the American Speech-Language-Hearing Association Convention, San Francisco, CA.

Bradley, J. (1986). Speech intelligibility studies in classrooms. *Journal of the Acoustical Society of America, 80*, 846–854.

Crandell, C. (1991). Classroom acoustics for normal-hearing children: Implications for rehabilitation. *Educational Audiology Monographs, 2*, 18–38.

Crandell, C. (1992). Classroom acoustics for hearing-impaired children. *Journal of the Acoustical Society of America, 92*, 2470.

Crandell, C. (1993). Noise effects on the speech recognition of children with minimal hearing loss. *Ear and Hearing, 7*, 210–217.

Crandell, C., & Bess, F. (1986, October). Speech recognition of children in a “typical” classroom setting. *Asha, 29*, 87.

Crandell, C., & Flannagan, R. (1999). Effects of conductive hearing loss on speech recognition in quiet and noise. *Journal of Educational Audiology, 8*, 5–14.

Crandell, C., & Smaldino, J. (1992). Sound-field amplification in the classroom. *American Journal of Audiology*, *1*(4), 16–18.

Crandell, C., & Smaldino, J. (1994). The importance of room acoustics. In R. Tyler & D. Schum (Eds.), *Assistive listening devices for the hearing impaired* (pp. 142–164). Baltimore, MD: Williams & Wilkins.

Crandell, C., & Smaldino, J. (1995). An update of classroom acoustics for children with hearing impairment. *Volta Review, 1,* 4–12.

Crandell, C., & Smaldino, J. (1996). Sound field amplification in the classroom: Applied and theoretical issues. In F. Bess, J. Gravel, & A. Tharpe (Eds.), *Amplification for children with auditory deficits* (pp. 229–250). Nashville, TN: Bill Wilkerson Center Press.

Crandell, C., & Smaldino, J. (2000a). Assistive technologies for the hearing impaired. In R. Sandlin (Ed.), *Textbook of hearing aid amplification: Technical and clinical considerations* (2nd. ed., pp. 643–672). San Diego, CA: Singular Press.

Crandell, C., & Smaldino, J. (2000b). Room acoustics for listeners with normal hearing and hearing impairment. In M. Valente, R. Roeser, & H. Hosford-Dunn (Eds.), *Audiology treatment* (pp. 601–637). New York: Thieme Medical.

Crandell, C., Smaldino, J., & Flexer, C. (1995). *Sound field FM amplification: Theory and practical applications*. San Diego, CA: Singular Press.

Crook, M., & Langdon, F. (1974). The effects of aircraft noise in schools around London airport. *Journal of Sound and Vibration, 34,* 221–232.

Crum, D. (1974). *The effects of noise, reverberation, and speaker-to-listener distance on speech understanding*. Unpublished doctoral dissertation, Northwestern University, Evanston, IL.

Crum, D., & Matkin, N. (1976). Room acoustics: The forgotten variable. *Language, Speech, and Hearing Services in Schools, 7,* 106–110.

Dixon, P. (1976*). The effects of noise on children’s psychomotor, perceptual, and cognitive performance*. Unpublished doctoral dissertation, University of Michigan, Ann Arbor.

Elliott, L. (1979). Performance of children aged 9 to 17 years on a test of speech intelligibility in noise using sentence material with controlled word predictability. *Journal of the Acoustical Society of America, 66,* 651–653.

Elliott, L. (1982). Effects of noise on perception of speech by children and certain handicapped individuals. *Journal of Sound and Vibration, 12,* 9–14.

Elliott, L., Connors, S., Kille, E., Levin, S., Ball, K., & Katz, D. (1979). Children's understanding of monosyllabic nouns in quiet and in noise. *Journal of the Acoustical Society of America, 66,* 12–21.

Finitzo-Hieber, T. (1988). Classroom acoustics. In R. Roeser (Ed.), *Auditory disorders in school children* (2nd ed., pp. 221–233). New York: Thieme-Stratton.

Finitzo-Hieber, T., & Tillman, T. (1978). Room acoustics effects on monosyllabic word discrimination ability for normal and hearing-impaired children. *Journal of Speech and Hearing Research, 21,* 440–458.

Flexer, C. (1992). Classroom public address systems. In M. Ross (Ed.), *FM auditory training systems: Characteristics, selection and use* (pp. 189–209). Timonium, MD: York Press.

Fourcin, A., Joy, D., Kennedy, M., Knight, J., Knowles, S., Knox, E., Martin, M., Mort, J., Penton, J., Poole, D., Powell, C., & Watson, T. (1980). Design of educational facilities for deaf children. *British Journal of Audiology* (Suppl. 3), 1–58.

French, N., & Steinberg, J. (1947). Factors governing the intelligibility of speech sounds. *Journal of the Acoustical Society of America, 19*, 90–119.

Gengel, R. (1971). Acceptable signal-to-noise ratios for aided speech discrimination by the hearing impaired. *Journal of Auditory Research, 11*, 219–222.

Green, K., Pasternak, B., & Shore, B. (1982). Effects of aircraft noise on reading ability of school age children. *Archives of Environmental Health, 37,* 24–31.

Ko, N. (1979). Response of teachers to aircraft noise. *Journal of Sound and Vibration, 62*, 277–292.

Kodaras, M. (1960). Reverberation times of typical elementary school settings. *Noise Control, 6*, 17–19.

Koszarny, Z. (1978). Effects of aircraft noise on the mental functions of school children. *Archives of Acoustics, 3*, 85–86.

Leavitt, R., & Flexer, C. (1991). Speech degradation as measured by the Rapid Speech Transmission Index (RASTI). *Ear and Hearing, 12*, 115–118.

Lehman, A., & Gratiot, A. (1983). Effects du bruit sur les enfants a l'ecole. In *Proceedings of the 4th Congress on Noise as a Public Health Problem* (pp. 859–862). Milano: Centro Ricerche e Studi Amplifon.

Levitt, H., & Resnick, S. (1978). Speech perception by the hearing-impaired: Methods of testing and the development of new tests. *Scandinavian Audiology*, 6, 107–130.

Licklider, J., & Miller, G. (1951). The perception of speech. In S. Stevens (Ed.), *Handbook of experimental psychology* (pp. 52–65). New York: John Wiley.

Lochner, J., & Burger, J. (1964). The influence of reflections in auditorium acoustics. *Journal of Sound and Vibration, 4*, 426–454.

Markides, A. (1986). Speech levels and speech-to-noise ratios. *British Journal of Audiology, 20*, 115–120.

McCroskey, F., & Devens, J. (1975). Acoustic characteristics of public school classrooms constructed between 1890 and 1960. *NOISEXPO Proceedings,* 101–103.

Nabelek, A. (1982). Temporal distortions and noise considerations. In G. Studebaker & F. Bess (Eds.), *The Vanderbilt hearing aid report: State of the art research needs* (pp. 1242–1248). Upper Darby, PA: Monographs in Contemporary Audiology.

Nabelek, A., & Nabelek, I. (1994). Room acoustics and speech perception. In J. Katz (Ed.), *Handbook of clinical audiology* (4th ed, pp. 624–637). Baltimore, MD: Williams & Wilkins.

Nabelek, A., & Pickett, J. (1974a). Monaural and binaural speech perception through hearing aids under noise and reverberation with normal and hearing-impaired listeners. *Journal of Speech and Hearing Research, 17*, 724–739.

Nabelek, A., & Pickett, J. (1974b). Reception of consonants in a classroom as affected by monaural and binaural listening, noise, reverberation, and hearing aids. *Journal of the Acoustical Society of America, 56*, 628–639.

Neimoeller, A. (1968). Acoustical design of classrooms for the deaf. *American Annals of the Deaf, 113*, 1040–1045.

Nober, L., & Nober, E. (1975). Auditory discrimination of learning disabled children in quiet and classroom noise. *Journal of Learning Disabilities, 8*, 656–773.

Olsen, W. (1981). The effects of noise and reverberation on speech intelligibility. In F. Bess, B. Freeman, & J. Sinclair (Eds.), *Amplification in education* (pp. 225–236). Washington, DC: Alexander Graham Bell Association for the Deaf.

Olsen, W. (1988). Classroom acoustics for hearing-impaired children. In F. Bess (Ed.), *Hearing impairment in children* (pp. 266–277). Parkton, MD: York Press.

Paul, R. (1967). *An investigation of the effectiveness of hearing aid amplification in regular and special classrooms under instructional conditions*. Unpublished doctoral dissertation, Wayne State University, Detroit, MI.

Peutz, V. (1971). Articulation loss of consonants as a criterion for speech transmission in a room. *Journal of the Audio Engineering Society, 19,* 915–919

Sabine, W. (1964). *Collected papers on acoustics*. Dover Publications.

Sanders, D. (1965). Noise conditions in normal school classrooms. *Exceptional Children, 31*, 344–353.

Sapienza, C., Crandell, C., & Curtis, B. (1999). Effect of sound field FM amplification on vocal intensity in teachers. *Journal of Voice, 23*, 101–110.

Sargent, J., Gidman, M., Humphreys, M., & Utley, W. (1980). The disturbance caused by schoolteachers to noise. *Journal of Sound and Vibration, 62*, 277–292.

Siebein, G. (1994). *Acoustics in buildings: A tutorial on architectural acoustics*. New York: Acoustical Society of America.

Siebein, G., Crandell, C., & Gold, M. (1997). Principles of classroom acoustics: Reverberation. *Educational Audiology Monographs, 5*, 32–43.

Received September 27, 1999
Accepted June 30, 2000

Contact author: Carl C. Crandell, Department of Communication Processes and Disorders, University of Florida, 461 Dauer Hall, Gainesville, FL, 32611. Email: crandell@csd.ufl.edu