

An Exploration of Non-Quiet Listening at School

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The first goal of this study was to describe acoustic properties across an entire day in each of three educational environments: daycare (pre-kindergarten), an elementary school (kindergarten to grade 8), and a high school (grades 9 through 12). Instructional and non-instructional listening situations were included in this description. Second, we classified the various listening situations experienced by the cohorts at each school. Three sites participated in this study. At each site, empty room measurements were obtained, including noise floor and reverberation levels, across the various rooms frequently occupied by the participating cohorts of children. Next, the first author followed the cohorts throughout their regular school routines, recording sound level data with a dosimeter and documenting observations of the types of listening situations encountered by the children. Noise floor, reverberation, and sound levels were compared to classroom standards and large scale classroom studies. The cohorts in this study encountered highly variable acoustic environments throughout the day, for signal levels, noise sources, and reverberation properties. These results have implications for digital signal processing and hearing instrument fitting approaches for school-age children. Furthermore, the results of this exploratory study may impact on future research on classroom acoustics.

Introduction

The purpose of the current study was to gather detailed information about the school-day listening environments of three cohorts of children in mainstream educational environments. This study served as a precursor to a larger study investigating hearing instrument fitting strategies for children in non-quiet listening environments and situations. Modern hearing instruments typically offer some combination of frequency-gain adjustment, directional microphones, and digital noise reduction (DNR) with the goal of providing better speech recognition and listening comfort/tolerance in noise. While research has demonstrated that directional microphones can improve children's speech recognition in noise performance (Auriemma et al., 2009; Gravel, Fausel, Liskow, & Chobot, 1999; Kuk, Kollofski, Brown, Melum, & Rosenthal, 1999), the use of DNR with children has not demonstrated any measureable improvement (Pittman, 2011; Stelmachowicz et al., 2010). These results are consistent with similar findings in adult listeners, and have led to mixed recommendations regarding the use of directional microphones and DNR in pediatric hearing instrument fittings. Some guidelines do not recommend using these features (AAA, 2003), whereas others consider them viable options (Bagatto, Scollie, Hyde, & Seewald, 2010; CASLPO, 2002; Foley, Cameron, & Hostler, 2009) or recommend directional microphones universally (King, 2010).

As part of an overall project investigating strategies to improve children's hearing instrument fittings for non-quiet listening, the current study explored the daily listening experiences of children over an entire school day. This exploration included

situations beyond the classroom situation of listening to a teacher. This may be an informative first step in determining optimal signal processing for children in non-quiet environments.

Studies of adults who wear hearing instruments have applied the concept of auditory ecology (Gatehouse, Elberling, & Naylor, 1999; Gatehouse, Naylor, & Elberling, 2003, 2006a, b), a concept in which the sound levels across a real-life, real-time sample from an individual hearing instrument wearer are used to inform hearing instrument signal processing choices. This study used an auditory ecology measurement approach in a small number of classroom cohorts. We measured reverberation time (RT) and noise floor levels across the many school environments. Additionally, we measured sound levels across an entire day, rather than a large scale sampling of sound levels during only targeted (typically classroom) listening situations. This ecological approach allowed the description of both instructional and non-instructional parts of the day, which may serve to improve hearing instrument fitting practices for children attending school. For example, listening to a friend while playing outside is an important listening situation, and one that is not well described in the classroom acoustics literature. This paper presents data across all listening environments and situations encountered by three cohorts of children.

Auditory Ecology: Children in Non-Quiet Environments

Auditory ecology has been defined as the range of acoustical environments that a person experiences, the auditory demands of those environments, and the importance of those demands to an individual's daily life (Gatehouse, et al., 1999; Gatehouse, et al., 2003, 2006a, b). A hearing instrument's ability to support multi-

environment listening is a significant predictor of hearing instrument benefit in adults (Hickson, Clutterbuck, & Khan, 2010; Kochkin, 2005). A recent study of hearing instrument outcome in children suggests that multi-environment listening is also important for children. The study compared two hearing instrument prescriptive algorithms in a sample of school-age children with hearing loss; results are reported across several publications (Ching, Scollie, Dillon, & Seewald, 2010; Ching et al., 2010a; Ching et al., 2010b; Scollie et al., 2010).

Although auditory ecology was not a specific focus of the study, insight into the varied auditory environments experienced by children arose from the diary entries reported in Scollie et al. (2010). The authors sought to identify a relationship between prescription preferences and the different listening situations encountered by the children by performing a principal components analysis on the children's preference ratings. From this analysis, two components emerged that contained several listening environments each. The first component consisted of loud, noisy, and reverberant situations: shopping mall, restaurant, car/bus/train, playground, family at home, watching TV or a movie, friends in class, and teacher in class. The second component consisted of quiet, or low-level, listening situations: friends in class, soft speech, sounds from behind, teacher in class, and sounds in the environment (Scollie et al., 2010). Interestingly, the classroom listening ratings were correlated with both components, suggesting that the classroom environment presents situations that vary between quiet and noisy. Overall, the results indicated that children need hearing instrument strategies that effectively manage listening in noisy situations, as well as strategies that optimize speech intelligibility in quiet or communication-intensive situations (Scollie et al., 2010). Considering the significant amount of time children spend in school, the current study focused on exploring children's listening environments and situations encountered in that environment. Although this was not primarily a study of classroom acoustics per se, traditional measures of room acoustics were included to allow for a description of the children's classrooms and are defined below.

Room Acoustics

The characteristics of a speech signal, and the ability of listeners to understand the speech signal, depend in part on the acoustic properties of the room in which the signal is presented. There are multiple factors to consider when classifying a room, such as the level of background noise, the level of the talker, the amount of reverberation in the room, and the distance of the talker from the listener (Boothroyd, 2004; Crandell & Smaldino, 2000; Finitzo-Hieber & Tillman, 1978; Nábělek & Nábělek, 1994; Nelson & Soli, 2000; Smaldino, Crandell, Brian, Kreisman, &

Kreisman, 2008). The various acoustic properties of a room have also been shown to have differential effects on listeners depending on age and hearing status, such that younger children and children with hearing loss are more affected by increased RT and decreased signal-to-noise ratio (SNR: Boothroyd, 2004; Finitzo-Hieber & Tillman, 1978; Nábělek & Nábělek, 1994; Nelson & Soli, 2000; Smaldino, et al., 2008). The implications, importance, and measurement of classroom acoustics have been widely documented in the literature (Finitzo-Hieber & Tillman, 1978; Knecht, Nelson, Whitelaw, & Feth, 2002; Larsen & Blair, 2008; Nelson, Smaldino, Erler, & Garstecki, 2008; Nelson & Soli, 2000; Picard & Bradley, 2001; Pugh, Miura, & Asahara, 2006; Shield & Dockrell, 2004).

Background noise generally refers to any sound that interferes with or impedes what a listener wants or needs to hear (Knecht, et al., 2002; Smaldino, et al., 2008). Examples of background noise include sounds from sources within a room (e.g., ventilation systems, computer fans, and overhead projectors), sounds from external sources (e.g., traffic noise, grounds maintenance equipment, and sound made by people in adjacent rooms or outside the building), as well as sounds made by the children themselves. Background noise negatively affects speech recognition ability by reducing the audibility of acoustic cues present in a speech signal that are important for understanding and distinguishing speech sounds (Smaldino, et al., 2008). The level of background noise present in classrooms has been the focus of many classroom acoustic studies and has been reported to range from under 30 dBA to over 70 dBA (Crandell & Smaldino, 1994; Knecht, et al., 2002; Nelson, et al., 2008; Pearsons, Bennett, & Fidell, 1977; Pugh, et al., 2006). The presence of students generally increases the level of noise in a classroom, with increases in noise levels varying from approximately 2dBA to 30 dBA between unoccupied and occupied classrooms (Bess, Sinclair, & Riggs, 1984; Hodgson, 1994; Picard & Bradley, 2001).

In order to be understood clearly, the level of speech in a given environment must be sufficiently above the level of background noise. The level of speech relative to the level of background noise is typically expressed as SNR, which represents the difference (in dB) between the level of the speech signal and the background noise level. The SNR encountered in classrooms can range from -7 to +15 dB (Blair, 1977; Crandell & Smaldino, 2000; Houtgast, 1981; Markides, 1986; Pearsons, et al., 1977), which may indicate that children often listen at SNRs poorer than the recommended minimum of +15 dB SNR for educational settings (ASHA, 2005). Additionally, the effects of reverberation in the room and distance from the talker can impact whether the speech-to-competition ratio is sufficient for speech understanding.

Reverberation is the persistence of sound energy in a room due to reflections of the sound energy from floors, ceilings, and

objects in the room. Reverberation time, specifically RT_{60} , refers to the length of time required for the level of an emitted sound (at a particular frequency) to decrease by 60 dB after the signal is stopped. RT is dependent upon the size and shape of a room, as well as the sound absorptive properties of the walls, ceilings, and objects within the room (Boothroyd, 2004; Nábělek & Nábělek, 1994; Smaldino, et al., 2008). Measurement of RT in classrooms has been reported to range from 0.4s to 1.2s. For comparison, audiometric test booths typically have RTs of approximately 0.2s, living rooms and offices can have RTs of 0.4s to 0.8s, while auditoriums and churches can have RTs greater than 3.0s (Nábělek & Nábělek, 1994; Smaldino, et al., 2008). In general, the ability to understand speech in a room decreases with increasing RT (Nábělek & Nábělek, 1994; Smaldino, et al., 2008); however, it is important to consider the interactions between background noise sources, reverberation, and the distance between talker and listener due to the synergistic effects of these variables.

The acoustics of a speech signal change over distance and the sound arriving at the location of the listener is typically divided into direct and reflected energy components (Boothroyd, 2004; Crandell & Smaldino, 2000; Nábělek & Nábělek, 1994; Smaldino, et al., 2008). Direct sound energy consists of sound waves that travel straight to the listener, without reflecting off any surfaces in the room. Reflected energy can be divided into two types (a) early reflections, which are sound waves that reach the listener shortly after the direct sound (approximately 50msec), and (b) late reflections, which arrive at the listener after reflecting off of multiple surfaces in the room. Depending on the distance from the talker and the characteristics of the room, the signal arriving at the listener may be predominantly direct sound energy, a mixture of direct and reflected energy, or predominantly reflected energy. Critical Distance (D_c) is the point in a room where the direct sound energy is equal to the reflected sound energy; at locations closer than D_c , the effects of reverberation are minimized. However, at locations further than D_c , reflected energy can interfere with (or mask) the primary speech signal, which makes understanding difficult. In general, speech understanding decreases with increasing distance from the talker until D_c is reached. Beyond D_c , performance is degraded but relatively constant with increasing distance. In order to maximize speech understanding, the distance between talker and listener should be minimized and remain within D_c (Boothroyd, 2004; Crandell & Smaldino, 2000; Nábělek & Nábělek, 1994; Smaldino, et al., 2008).

The American National Standards Institute (ANSI) has outlined recommended acoustic criteria for classrooms (ANSI S12.60, 2010). This standard recommends a maximum background noise level of 35 dBA and a maximum RT_{60} of 0.6s for classrooms with an enclosed volume of less than 283m³ (10 000 ft³); for larger

classrooms, the background noise level recommendation remains at 35 dBA with the recommended maximum RT_{60} increased to 0.7s. In studies of background noise levels and RT in classrooms, the majority of classrooms surveyed meet ANSI recommendations (ANSI S12.60, 2010) for RT_{60} , but they fail to meet background noise level criteria (Knecht, et al., 2002; Nelson, et al., 2008; Pugh, et al., 2006).

Children with hearing loss require a louder speech signal, higher SNR, and lower RT than their peers with normal hearing (Boothroyd, 2004; Elliott, 1979; Fallon, Trehub, & Schneider, 2002; Nábělek & Nábělek, 1994; Neuman, Wroblewski, Hajicek, & Rubinstein, 2010; Scollie, 2008; Smaldino, et al., 2008). To facilitate listening during formal classroom instruction, a wireless microphone can be worn by the teacher to enhance children's speech understanding. The remote microphone sends signals to the child's listening device(s) (hearing instruments or other devices) via frequency modulation (FM) signal transmission. This strategy is effective in overcoming the effects of background noise, room reverberation, and teacher-to-student distance (Boothroyd & Iglehart, 1998; Hawkins, 1984; Lewis, Feigin, Karasek, & Stelmachowicz, 1991; Pittman, Lewis, Hoover, & Stelmachowicz, 1999; Thibodeau, 2010). However, children experience many situations in which the primary signal of interest is not an individual teacher: playing at recess, team games in gym class, and conversations in the hallway between classes are all examples. In these situations, children may not be using an FM system; however, they are likely still using their hearing instruments. Thus, to inform hearing instrument development and fitting processes, and ultimately improve the validity of pediatric prescriptive algorithms, an understanding of the complex listening needs of children at school (which extends beyond the existing literature on classroom acoustics) is needed.

Purpose and Research Questions

The purpose of this study was to describe the acoustic environments and listening situations encountered by children across an entire day at school or daycare. The goal of this study was not to replicate prior studies of classroom acoustics; however, some classroom acoustics data are presented to contextualize the main purpose of this research. The purpose of this research was to explore the daily listening needs of children at school beyond instructional time. This study sought to address the following research question: What are the instructional and non-instructional listening situations experienced by school-age children throughout a school day? By situations, we mean signal and noise types, along with sources and levels. In addressing this question, some basic room acoustics data were also obtained. These measurements are compared to those reported in the literature of larger-scale classroom acoustics, in order to determine the representativeness of the chosen sites of study.

Method

Study Sites

Three sites in London, Ontario, Canada were studied, with approval from The University of Western Ontario's Health Sciences Research Ethics Board and appropriate officials of the local school board and daycare center. The school sites included an elementary school (kindergarten to grade 8, ages 5 to 14 years) and a high school (grades 9 to 12, ages 13 to 18 years) that support children with hearing loss through hearing resource programs (taught by teachers of the deaf and hard of hearing) within a mainstream school setting. These two sites were chosen because the cohorts of students who use hearing instruments at these two sites would ultimately participate in a future study of hearing instrument fitting for non-quiet environments. The third site, a daycare (ages 3 months to 5 years), was chosen to broaden the range of ages and environment types included.

Procedures

Unoccupied room measurements. The study began with acoustic measurements being made around the school and classroom environments encountered by students on a daily basis; these measurements were taken in unoccupied spaces after hours. Specifically, the level and spectra of the noise floor (dBA), as well as estimates of the reverberation time (RT_{60}) in each space, were measured. These measurements were taken with a portable system consisting of a laptop (LG R405G) running SpectraPLUS version 5.0.26.0 (Pioneer Hill Software LLC, 2008) connected to an external sound card (Sound Devices, LLC – USBPre). SpectraPLUS is an acoustic signal analysis software suite. The suite includes a spectrum analyzer with up to 24 bit precision in both real-time and post-processing modes and performs signal analysis with 1/1- to 1/96-octave bandwidths and fast Fourier transform (FFT) sizes of 32 through 1,048,576 points. The spectral analysis software can also perform spectral ANSI weighting (flat, A, B, and C) and total power calculation of acoustic signals. SpectraPLUS also includes a reverberation time utility that generates and presents a broadband signal while automatically recording the level of acoustic energy in a room over a specified time interval; this utility is used for estimating the reverberation time of rooms.

An AKG C4000B condenser microphone (1-inch dual-diaphragm condenser transducer

with a selected omnidirectional polar pattern) was used for recording all signals. A powered speaker (Simeon 500WU) was used for stimulus presentation in the RT_{60} estimates.

Noise floor measurements were performed by positioning the recording microphone in the center of the room and then recording a 30 second sample with SpectraPLUS. Post-processing was then done with SpectraPLUS to calculate the noise floor level (in dBA) and the spectral distribution of the noise.

Reverberation time estimates were made by positioning the recording microphone in the center of the room and then positioning the presentation speaker at the same height and approximately two meters from the microphone. Measurements were controlled by the Reverberation Module of SpectraPLUS set to estimate RT_{60} based on RT_{20} (Pioneer Hill Software LLC, 2008). A total of three reverberation time measurements were conducted in each space; the results were then averaged to provide an estimate of RT_{60} for the corresponding space. Table 1 summarizes general characteristics of the various rooms across the three sites, including whether rooms had carpet or tiles, windows with or without curtains, and/or active ventilation systems.

Observation and dosimetry phase. After completion of the unoccupied acoustic measurements, the observation phase of the study began. Students were observed and shadowed at each of the three sites for several school days. Sound samples of occupied spaces were recorded during observations with the portable laptop system equipped with SpectraPLUS; the equipment was set to record with a bandwidth of 20Hz to 20,000Hz. The portable

Table 1. Room characteristics across sites.

Room	Floor	Windows	Ventilation System
Elementary school			
Mainstream classroom	Tile	Yes, curtains	No
Hearing resource classroom	Carpet	Yes, curtains	No
Music room	Tile	None	Yes
Computer room	Tile	None	Yes
High school			
Mainstream classroom	Tile	None	Yes
Hearing resource classroom	Carpet	Yes, curtains	No
Computer room	Carpet	None	No
Daycare			
Infant room	Tile	Yes, no curtains	No
Toddler room	Tile	Yes, no curtains	No
Pre-school room	Tile	Yes, no curtains	No

Note: "Ventilation System" refers to active systems with fans or blowers emitting noise at levels greater than 40 dBA. While all classrooms had air circulation, only some had audible (greater than 40 dBA) ventilation noise; rooms with audible ventilation system noise are marked as "Yes" and those without audible systems are marked as "No."

system was used to record sound samples during lesson periods, nutrition breaks, and at recess. The collected sound samples were then post-processed with SpectraPLUS to calculate the noise level (in dBA) and spectral distribution of the acoustic environment. MATLAB (The Mathworks Inc., 2004) was used to estimate the SNR of teachers' voices during lesson periods in classrooms at the elementary and high school sites. This was done by calculating the variance of the noise component of the recorded signal using samples taken during pauses in the teachers' speech and then calculating the variance of the speech signal by subtracting the noise component variance from the variance of the total recorded signal. Since variance is proportional to intensity (or power) and SNR is defined as the ratio of intensities, the ratio of variances was used to calculate SNR from the recordings. The SNR estimates from two to three recordings in each lesson were then averaged. SNR was not estimated for the daycare rooms because education for children in daycares is play-based, rather than lesson- or lecture-based, as recommended by the Ontario provincial government (Best Start Expert Panel on Early Learning, 2007).

A Larson Davis Spark 706, Type 2 dosimeter was used during observations in order to record the sound levels experienced by students over the course of their days at school. The dosimeter was worn by an experimenter who attended all classes and activities along with the cohorts of children. The dosimeter microphone was positioned on the observer's left shoulder in order to have the microphone as close as possible to the left ear. The device was set to record the level in dBA at 10-second intervals over the duration of the school day; the length of the school day varied by site (daycare, elementary school, and high school). Data are reported in equivalent sound level (L_{eq}) which is the average of the sound levels (in dBA) for each 10-second recording interval.

Written notes were made during observations to classify the type of listening situation the students were in at any particular moment as: (a) "quiet" when there was no audible background noise or an overall level below 50 dBA, (b) "speech alone" when there was a single primary talker amidst no audible background noise, (c) "speech in noise" when there was a speech signal of interest (from one or more talkers) amidst audible background noise, (d) or "noise alone" when the only acoustic signal consisted of only undesired sound with no speech. Sources of noise (such as computer fans, traffic noise, and ventilation systems) were also noted. A similar method has been used by Ricketts, Picou, Galster, Federman, & Sladen (2010) in the evaluation of children's use of directional microphone technology.

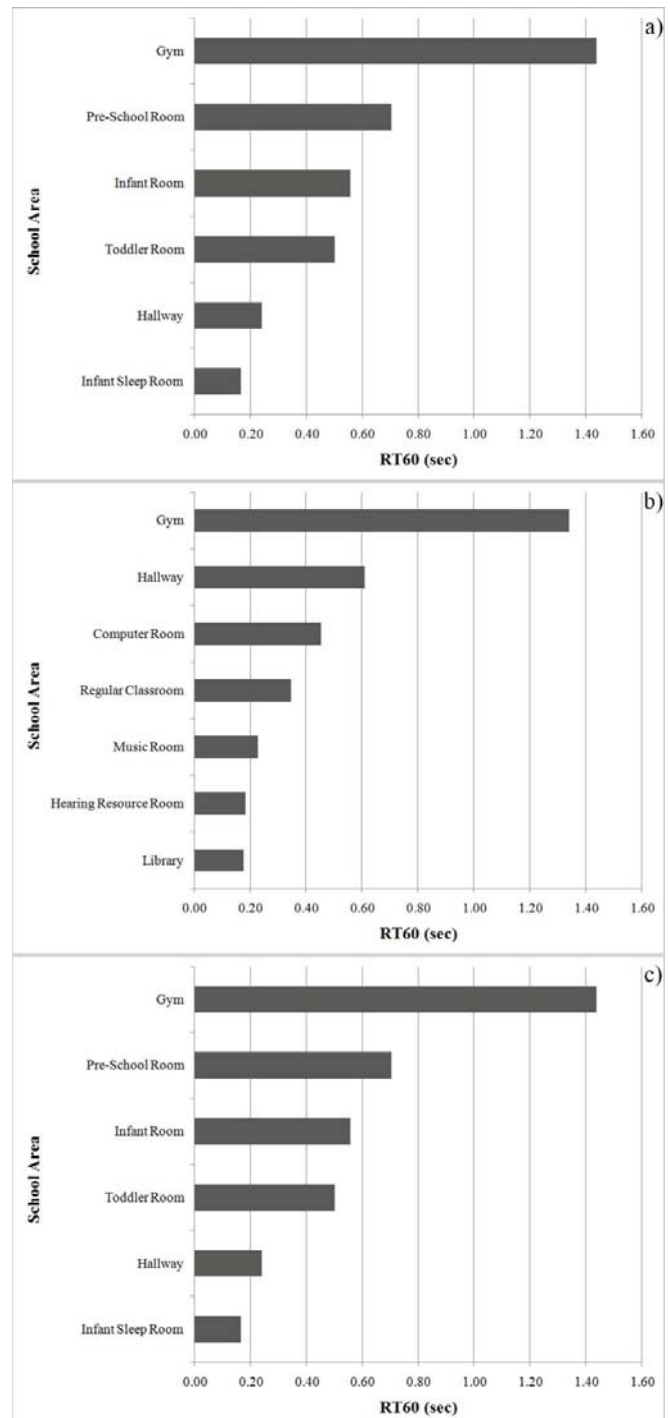
Results

Reverberation Time across School-Day Settings

Reverberation time (RT_{60}) data showed a wide range of

values across all three sites (Figure 1). In general, core learning areas (such as classrooms, computer rooms, and hearing resource rooms) demonstrated RT_{60} of under 0.6s. This indicates that the primary instructional environments in the schools measured were in compliance with ANSI recommendations. Gymnasium demonstrated large RT_{60} values of over 1.0s at all three sites.

Figure 1. Bar graphs showing reverberation time (RT_{60}) for various rooms at the daycare (panel a), elementary (panel b), and high school (panel c) sites.



Hallways at the elementary and high school sites demonstrated relatively high RT_{60} values, whereas the hallway at the daycare demonstrated a relatively low RT_{60} . This difference is likely due to low ceilings in the daycare hallway and numerous articles of clothing lining the hallway, which would act to absorb sound reflections. However, areas such as gymnasias and hallways are not considered “core learning areas” and, therefore, are not within the scope of the ANSI S12.60 (2010) recommendations.

Spectral Characteristics across School-Day Settings and Situations

Spectral data from classrooms at all three sites showed a broad range in level (Figure 2). Dosimetry data (presented later) offer explanations of some of the spectral results. The unoccupied noise levels in the daycare and elementary school were similar, while the noise floor of the high school classroom was more than 10 dB higher. This difference was likely due to the ventilation system being present in the high school classroom, which remained active for most of the school day. The levels and shape of the noise present while students were engaged in individual seatwork were similar in the elementary and high school classrooms; the pattern appears similar during the naptime of the pre-school children at the daycare with the exception of less low frequency energy at the daycare. Written observation data indicated that music was played throughout the entire naptime period. The highest overall level (71 dBA) was seen when the pre-school daycare children were engaged in indoor activities, with the majority of the energy in the mid-frequency region. Mid-frequency emphasis is characteristic of a raised vocal effort in the speech of both adults and children (Pearsons, et al., 1977).

Table 2 shows SNR estimates for a number of classroom settings, along with the corresponding RT_{60} and unoccupied noise floor estimates. A range of SNRs are seen across the rooms at both the high school and elementary school sites. The competing noise from computers and ventilation systems in the elementary school’s music and computer rooms result in low SNRs of only +5 dB. The SNRs of male teachers’ lessons in regular classrooms and lessons in the hearing resource classrooms of both sites were the highest estimates collected. The elementary school had a broader range of unoccupied noise floor levels relative to rooms measured at the high school. The difference between the lowest and highest noise floor levels was 23 dB at the elementary school and only 6 dB at the high school. The hearing resource classrooms at both sites had low reverberation times and noise floors. Although both hearing resource rooms were carpeted and had curtains for the windows, the room at the elementary school was also equipped with acoustic ceiling tiles and acoustic panels on the walls; these additions provide extra sound absorption and contribute to the

elementary school hearing resource classroom’s low RT_{60} . The hearing resource rooms at both sites had similar noise floor levels and similar SNRs during instruction. The addition of carpet and window treatments in both hearing resource rooms were likely the main factors contributing to the lower RT_{60} , thus the improved listening environment, of those rooms relative to the mainstream classrooms.

Figure 2. Amplitude spectra of sound sources at each observation site: pre-school room at daycare (panel a), elementary school classroom (panel b), and high school classroom (panel c). Overall level is shown above each curve.

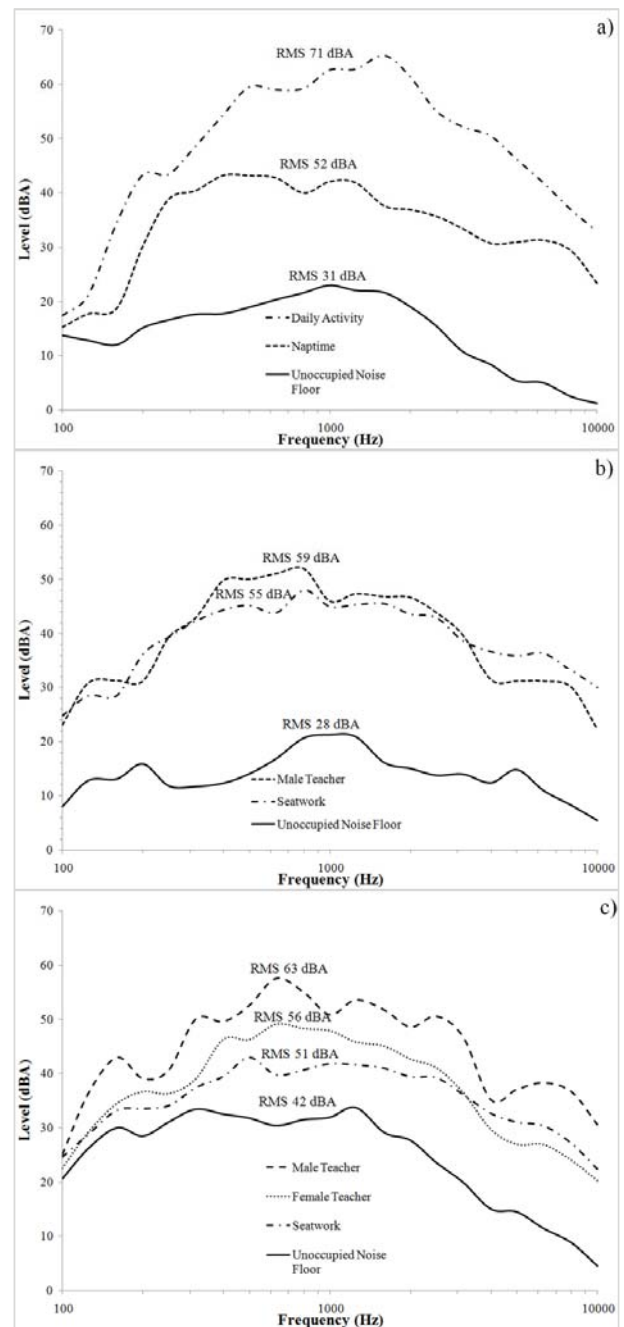


Table 2. Acoustic characteristics of classrooms across sites.

Room	RT60 (sec)	Unoccupied Noise Floor (dBA)	Average SNR (dB)
Elementary school			
Mainstream classroom	0.35	29	13 ^a
Hearing resource classroom	0.18	32	12 ^b
Music room	0.23	45	5 ^b
Computer room	0.45	52	5 ^b
High school			
Mainstream classroom	0.53	41	12 ^{a, 8} ^b
Hearing resource classroom	0.34	35	11 ^b
Computer room	0.30	35	11 ^b
Daycare			
Infant room	0.56	37	n/a
Toddler room	0.50	34	n/a
Pre-school room	0.70	31	n/a

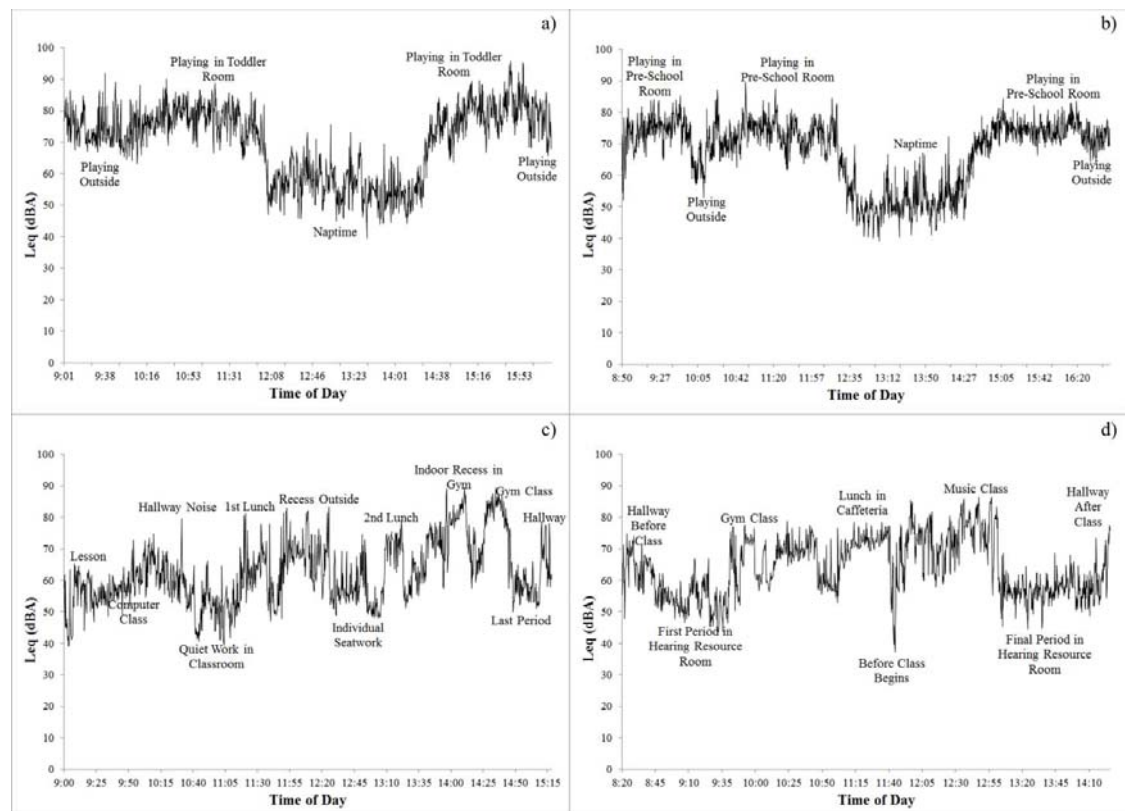
^a Male teacher^b Female teacher

There were notable differences between the elementary and high school computer rooms, as shown in Tables 1 and 2. The high school computer room had a lower RT_{60} , lower noise floor, and higher SNR, relative to the elementary school computer room. The elementary school computer room was not carpeted and was equipped with an active ventilation unit. These factors contributed to the higher RT_{60} and noise floor, which in turn contributed to the lower SNR of the elementary school computer room relative to the carpeted computer room at the high school (which did not contain a ventilation unit). As mentioned previously, SNR was not estimated for the daycare rooms due to the play-based, rather than lesson- or lecture-based, curricula (Best Start Expert Panel on Early Learning, 2007).

Sound Levels and Sources across the School Day

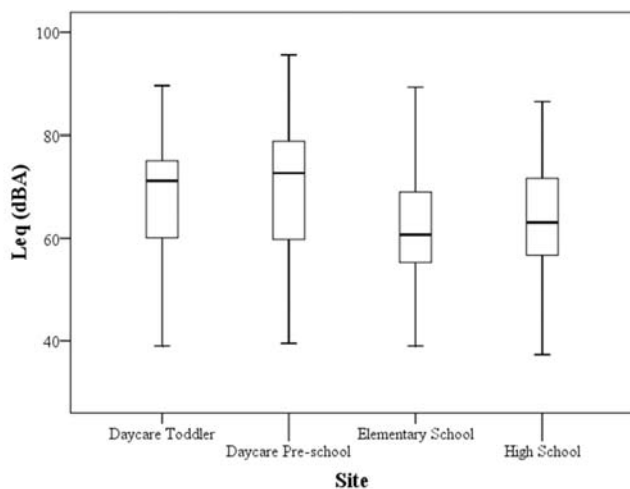
Dosimetry data show a large degree of variation in sound levels and listening environments and situations over the course of a school day across all three sites (Figure 3). The youngest group of children (toddlers) experienced the highest levels of all (panel a), followed by the pre-school children at the daycare (panel b), with both groups of children experiencing maximum L_{eq} levels of 90 dBA or higher. The daycare data show more sustained and higher levels than the elementary (panel c) or high school (panel d) sites. The daycare children of both age groups also show the same pattern of lower levels during naptime. The elementary and high school sites show more frequent variation in sound levels over the course of their school days, although lower in level, when compared to the daycare children.

Figure 3. Dosimetry data shown as L_{eqA} by time at each observation site: toddler room at daycare (panel a), pre-school room at daycare (panel b), elementary school (panel c), and high school (panel d). L_{eq} curves are labeled with events and environments from observation records.



Dosimetry data may be summarized as the distribution of sound levels (L_{eq}) over time. The L_{eq} distributions are shown as box plots in Figure 4. In this figure, the box encloses the central 50% of the data points. The solid line within the box represents the median; the lower edge of the box represents the lower quartile (25th percentile), with the upper edge of the box representing the upper quartile (75th percentile). Lines extend from the ends of the box to the maximum and minimum data points above and below the box respectively. Similar to the dosimetry L_{eq} graphs, the box plots show a large range of levels over the course of a day, with minimum values of 40 dBA and maximum values higher than 90 dBA. The higher levels in the daycare, relative to the elementary and high school sites, are apparent from the median points, with daycare children experiencing higher sound levels than the elementary and high school children.

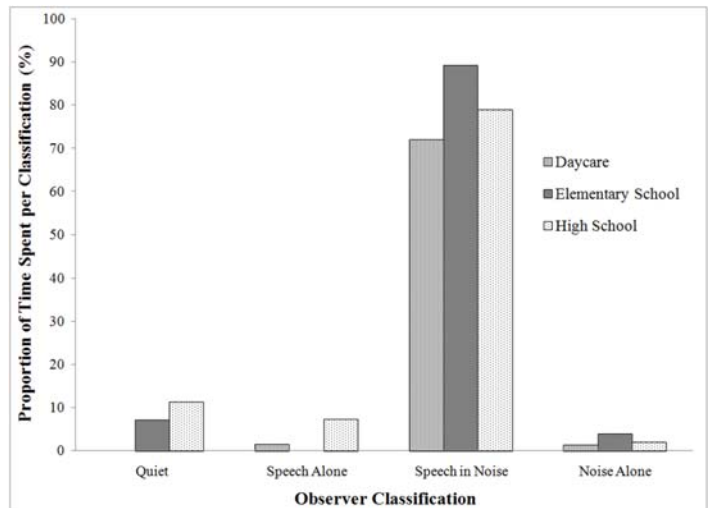
Figure 4. Boxplots depicting the L_{eq} data for each observation site.



Charted notes made during the observations were analyzed to yield the proportion of time the children spent in several environments (Figure 5). On average, children spent 80% of their total time in a mixture of speech in noise across the three sites, and seldom were in situations classified as quiet, speech alone, or noise alone (4% of total time, on average). In the daycare setting, there was no time considered to be quiet (i.e., no background noise, or an overall level below 50 dBA) and in the elementary school there was no time considered to be speech alone. Sources of competing noise were similar across the three sites, according to the written observation data. These sources included active ventilation systems, fan noise from computers, traffic noise from outside, children's voices and lessons from the same and adjacent rooms, and activity in hallways outside of the classrooms.

It is worth emphasizing some of the observational results here. Referring to Figure 3 again, observations revealed the

Figure 5. Proportion of time spent in each sound environment, as classified by the observer for each site.



following listening environment-situation combinations. Daycare environments and situations included: outdoor play, indoor play, and naptime (indoor). Elementary school environments and situations included: instructional lessons in classrooms, instructional lessons in computer rooms, hallway noise (with communication attempts), quiet seatwork in classrooms, outdoor recess, lunch in classroom (with conversation), indoor recess in gymnasium, and gym class. High school environments and situations included: hallway noise (with communication attempts), resource periods in resource rooms, gym class, lunch in cafeteria (with conversation), and music class. In all of these situations, communication is occurring to varying degrees of success. Implications of the interaction of sound level, environment, and situation are worth considering for discussion.

Discussion

Auditory Ecology

The main contribution of this study is in its attention to the non-instructional listening situations that children encounter in their daily lives at school. This investigation revealed that children spend time in a variety of rooms, with a broad range of reverberation levels and spectral characteristics. Furthermore, the types and levels of sound sources that children experience throughout their school days are also quite diverse. The variability in noise levels between unoccupied and occupied classrooms has been well documented in the literature (Bess, et al., 1984; Hodgson, 1994; Picard & Bradley, 2001). However, the novel contribution of the current study is the application of the concept of auditory ecology to school day listening. The data presented illustrate and detail the range of acoustic environments and situations, as well as the challenges inherent in each, which children experience at school. Implications of these results will be discussed in the

context of hearing aid fittings. This discussion offers an exploration of auditory ecology of children in the school setting, which may inform future hearing instrument fitting approaches.

Although the current study was not an attempt to replicate prior large-scale classroom acoustics research, results suggest that the cohorts experienced representative classroom acoustics, with average noise floor and RT_{60} measurements resembling those of Knetch et al. (2002) and Larsen and Blair (2008). The purpose of collecting RT_{60} and spectral data in the current study was to provide a frame in which to view the dosimetry data, which were collected in order to evaluate the auditory ecology of the children in the study.

The work of Gatehouse et al. (1999; 2003, 2006a, b) demonstrated the importance of considering an individual's auditory ecology in hearing instrument fittings and candidacy. Results of the Gatehouse et al. (1999; 2003, 2006a, b) study indicated differential benefit from hearing instrument processing strategies directly related to the diversity in participants' auditory ecology. The current study's combined data from dosimeter readings and observation notes demonstrate the broad range of environment-situation combinations influencing auditory ecology for the cohorts of children in the present study. For example, these data may suggest that existing practice guidelines which recommend a single hearing instrument listening program (optimized for communication-intensive environments [AAA, 2003; CASLPO, 2002]) may not adequately serve children across the diverse range of their auditory ecology. Rather, children may benefit from an additional listening program that has been optimized to address non-quiet listening needs.

Implications for Hearing Instruments

Current practice guidelines are mixed with regard to recommendations for noise management strategies in pediatric hearing instrument fittings. Some sources state that there is insufficient evidence to warrant use of advanced processing (AAA, 2003; Foley, et al., 2009), others consider these strategies viable options (Bagatto, et al., 2010; CASLPO, 2002), while others recommend features such as directional microphones ubiquitously (King, 2010). Two strategies commonly used for adults include directional microphones and digital noise reduction (DNR). In adults and children, use of directional microphones has been shown to improve speech understanding when the speech signal is in front and noise comes from the back or sides of the listener (Amlani, 2001; Auriemma, et al., 2009; Bentler, 2005; Gravel, et al., 1999; Hawkins & Yacullo, 1984; Hornsby & Ricketts, 2007a; Hornsby & Ricketts, 2007b; Kuk, et al., 1999; Ricketts, 2000, 2001; Ricketts, 2005). However, in those situations, the listener is expected to point his or her head toward the talker; close range listening is also

assumed. Therefore, the classroom environment may not allow children to benefit from directional microphones, as talker distance and location may not be frontal or within appropriate distance. Head orientation during note-taking, for example, has been shown to limit directional benefit (Ricketts & Galster, 2008).

DNR has been shown to improve listening comfort but not speech understanding in noise for adults (Bentler & Chiou, 2006; Bentler, Wu, Kettel, & Hurtig, 2008; Bentler, 2005; Mueller, Weber, & Hornsby, 2006; Palmer, Bentler, & Mueller, 2006; Ricketts & Hornsby, 2005). Similarly, use of DNR has shown no improvement in children's recognition of speech-in-noise (Pittman, 2011; Stelmachowicz, et al., 2010). Thus, this technology may not provide adequate speech understanding in the classroom; FM systems are, therefore, preferred (AAA, 2003; CASLPO, 2002).

For these reasons, typical noise management technologies may be difficult to apply for children, or may offer insufficient benefits, particularly during instruction. Children, nonetheless, experience situations of problematic loudness and/or noisiness that should be addressed in hearing instrument fittings (Scollie, et al., 2010). To address this need, loudness management strategies, such as a secondary listening program for use in noisy situations, have been suggested (Scollie et al., 2005, 2010). The present study describes the wide range of acoustic environments and listening situations encountered by children of three age ranges. This study was developed in order to inform future studies of hearing instrument signal processing for non-quiet and non-instructional periods of the school day.

Hearing instrument digital signal processors use signal classification algorithms to classify listening situations as either "speech," "noise," or other types of signals (e.g., wind or music). A notable result emerges from the combined data presented in Figure 4 and Figure 5. The data show that the vast majority of students' days are spent in "speech in noise" situations, across a variety of environments, rooms, and levels. Across the three sites, approximately 45% of speech in noise situations occurred at moderate sound levels (60 to 70 dBA).

The DNR systems available in commercial hearing instruments are typically activated by internal measurements of SNR, overall input level, or both (Bentler & Chiou, 2006; Chung, 2004). If a hearing instrument classifier assumes that "noise" only occurs in loud environments, there is potential for classification errors to occur (Chung, 2004). The data from this study may, therefore, serve to inform future work on hearing instrument signal processing for children by beginning to identify the range of SNRs and input levels children experience in their daily lives.

Likewise, audiologists typically fit hearing instruments for hearing in speech-dominated environments. In the classroom, school-age children who wear hearing instruments typically have

a personal FM system, which is an effective and optimal strategy for that situation. However, the results of this study show that children have substantial listening needs outside traditional classroom instruction or speech-dominated environments. This result aligns with the results of the Scollie et al. (2010) study, which reported a variety of listening needs and requirements that were best served by multiple hearing instrument listening programs. In certain situations (such as listening to a teacher or peer during hallway travel, playing team sports, and participating in dynamic group learning activities), use of a personal FM system may not be optimal or practical. In these situations, a secondary listening program that uses additional signal processing strategies (such as frequency-gain shaping, directional microphones, DNR, or a combination of these strategies) may be effective for improving loudness comfort and/or speech understanding. A secondary program can be either selected manually by the child or automatically by the hearing instrument processor. While there is some evidence that children can manually switch listening programs effectively and appropriately (Scollie, et al., 2010), others studies have shown that many children do not manually switch listening programs appropriately or at all (Ricketts, et al., 2010). Most modern hearing instruments offer automatic listening program switching, which uses the DSP classification system of the hearing instrument to make decisions regarding which listening program or microphone mode should be used. However, research suggests that current automatic switching systems may not be appropriate for children's use in school settings (Ricketts, et al., 2010). Therefore, while the implementation of secondary listening programs may address the diverse listening needs of children at school, clinicians need to consider the individual abilities of children when designing and implementing a secondary listening program in a pediatric fitting. The data presented in the current study may inform future work regarding the use of hearing instrument signal processing for children's listening needs across multiple environments.

Implications for Classroom Acoustics Research

Existing literature provides acoustic descriptions of static classroom acoustics and ANSI recommended criteria for classroom acoustics (Knecht, et al., 2002; Larsen & Blair, 2008; Nelson, et al., 2008). The current data generally agree with the existing literature demonstrating lower than recommended SNRs even in rooms which satisfy recommended RT_{60} and noise floor criteria. Although personal FM systems can assist students with hearing loss in situations with a low SNR, it is important to note that the ANSI S12.60 (2010) and ASHA (2005) recommendations apply to all school-age children regardless of hearing status. Furthermore, the current study suggests a need to consider the breadth of listening environments (multiple rooms and locations throughout a school day) and situations (teacher talking, classmates talking, music) that children encounter. This need is relevant to those interested in the importance of classroom acoustics

for optimal learning because not all of a child's formal learning takes place in a traditional classroom with a teacher's voice as the main signal of interest. However, the acoustic measurements and observation data reported in this study represent an admittedly small sample, with limited generalization abilities. It is suggested that future research pursue a large-scale investigation of the acoustics, dosimetry characteristics, or classification of non-classroom environments, for example.

Future Research

The primary focus of this work was to determine the range and types of listening situations children encounter across a school day, in order to provide context for future work in hearing instrument signal processing strategies for children with hearing loss. The results of this study have demonstrated that children experience a wide range of noise levels and types across a variety of listening environments and situations over the course of a school day. Classroom RT_{60} measurements were generally under the 0.6s maximum as recommended by ANSI S12.60 (2010). However, unoccupied noise floor levels ranged from several dB below, to almost 20 dB above the recommended 35 dBA noise level; estimates of SNR were generally below the +15 dB recommended by ASHA (2005). Notably, hearing resource rooms that had acoustic treatment demonstrated better acoustic properties than untreated rooms. The data support a need to consider and classify noise sources and levels encountered in a school day (such as class activity from adjacent rooms, students in the hallway, and low-level computer noise) in addition to the more traditional definitions of noise (such as machine and equipment noise). Limitations of the current study's sample size preclude statistical analysis and generalization. Yet, the sites selected are in agreement with the existing larger scale studies reported in the literature. Thus, it is possible to infer that other cohorts of children may be subject to similar amounts of variability in listening environments and situations.

Conclusions

In summary, these data describe the acoustical properties of a typical day at school. Results indicate that children regularly experience loud situations with levels in excess of 80 dBA, as well as moderate-level situations with poor SNRs. Raised vocal effort of teachers was also demonstrated in the results. Furthermore, children experience a wide range of listening needs dependent on the acoustic characteristics of the listening environment and the activity in which they are participating. Current hearing aid technology offers a variety of options for management of either loud sounds or sounds with a low SNR. Research investigating the application of secondary listening programs in pediatric hearing instrument fittings to assist listening in non-quiet environments and situations appears to be warranted.

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