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Non-Quiet Listening for Children with Hearing Loss: An Evaluation of Amplification Needs and Strategies

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A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Health and Rehabilitation Sciences

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NON-QUIET LISTENING FOR CHILDREN WITH HEARING LOSS: AN EVALUATION OF AMPLIFICATION NEEDS AND STRATEGIES

(Spine title: Non-Quiet Listening for Children with Hearing Loss)

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by

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Graduate Program in Health and Rehabilitation Sciences

A thesis submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

The School of Graduate and Postdoctoral Studies
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THE UNIVERSITY OF WESTERN ONTARIO
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Abstract

The goals of this project were to identify and evaluate strategies for managing the non-quiet listening needs of children with hearing loss who wear hearing instruments.

Three studies were undertaken: 1) an exploration of the listening environments and situations experienced by children from daycare to high school during the school-day; 2) a comparative evaluation of consonant recognition, sentence recognition in noise, and loudness perception with the Desired Sensation Level version 5 (DSL v5) Quiet and Noise prescriptions and 3) a comparative evaluation of sentence recognition in noise and loudness perception with DSL v5 Quiet and Noise paired with the hearing instrument features of directional microphone and digital noise reduction (DNR) technology.

The first study showed that children experience a wide variety of listening environments and situations, most of which can be classified as "non-quiet". This result confirms the need for the development of processing strategies for children listening in non-quiet environments and situations. The second study showed that the DSL v5 Noise prescription does not negatively impact consonant recognition except at low levels, with no significant differences in sentence recognition in noise. Improved comfort for loud sounds was afforded by DSL v5 Noise compared to DSL v5 Quiet. The third study showed that the optimal combination of prescription and hearing instrument features tested was DSL v5 Noise with a directional microphone.

The results of these three studies offer a starting point for the development of a protocol for providing a non-quiet listening strategy for children who wear hearing instruments. This result is a significant contribution to the currently discrepant guidelines across countries and pediatric audiology organizations.

Keywords: Audiology, child, digital signal processing, digital noise reduction, directional microphone, hearing aids, noise, outcome measurement

Co-Authorship Statement

I, Jeffery L. Crukley, acknowledge that this thesis includes three integrated manuscripts that were made possible by collaborative efforts. In the three manuscripts, the primary intellectual contributions were made by the first author who: researched the methodology, designed the research, developed the ethics application, conducted the literature reviews, established relationships with gatekeepers, and undertook the data collection, data analysis, and writing of the manuscripts. The first of the three manuscripts has been submitted for publication. The contribution of the co-author on all manuscripts, Dr. Susan Scollie, was primarily through the supervision of the research, theoretical and methodological guidance, and intellectual and editorial support in crafting the work for publication. Dr. Vijay Parsa, co-author on the first manuscript, offered guidance with signal analysis.

Dedication

This work is dedicated to my father.

I hope you are able to see the life you created and will forever inspire.

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Susan Scollie, thank you for your support and guidance through both the ups and downs of the doctoral process. You pushed me to overcome obstacles, to see the biggest picture possible, and to maintain optimism and enthusiasm. Thank you Susan, for being a mentor and a friend.

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To my family, I cannot express how vital your love and support have been to me over the years. Thank you, mom and Neil, for always being there.

The three studies presented in this dissertation would not have been possible without the collaboration and support of many teachers, support staff and students of the Thames Valley District School Board, including teachers of the deaf and hard of hearing and their educational assistants: Nancy Wren, Graham Bartlett, Ainsley Latour, BJ Rayner, and Deana McIntyre. Hearing Resource Team members: Stella Ng, Brenda Buckrell, Vickie Hlady-MacDonald, Mary Kay Horton, and the itinerant teachers of the deaf and hard of hearing.

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Chapter 1

1 Introduction

1.1 Purpose

The purpose of this dissertation was to advance understanding of children's listening needs in non-quiet listening situations, to evaluate outcomes of existing hearing instrument fitting strategies to support these needs, and to begin to develop an evidence-based approach to support the breadth of listening needs of children with hearing loss who wear hearing instruments.

1.2 Background

The use of hearing instruments as an early intervention strategy for children with hearing loss has been shown to foster speech and language development, academic performance, as well as social and emotional development (Carney & Moeller, 1998; Moeller, 2000; Moeller, Donaghy, Beauchaine, Lewis, & Stelmachowicz, 1996; Moeller, Tomblin, Yoshinaga-Itano, Connor, & Jerger, 2007; Vohr et al., 2008; Yoshinaga-Itano, Johnson, Carpenter, & Brown, 2008). Hearing instrument prescriptive algorithms typically provide suitable audibility (Cornelisse, Seewald, & Jamieson, 1995; Jenstad et al., 2007; Jenstad, Seewald, Cornelisse, & Shantz, 1999; Scollie, 2008; Scollie et al., 2010b; Scollie et al., 2005; Seewald, Ross, & Spiro, 1985) and listening comfort for speech signals (Cornelisse et al., 1995; Jenstad et al., 2007; Jenstad, Pumford, Seewald, & Cornelisse, 2000; Scollie et al., 2010b; Scollie, Seewald, Moodie, & Dekok, 2000). However, presenting the level of amplified speech adequately above the level of competing sound sources is difficult and a cause for concern with modern hearing instruments (Gravel, Fausel, Liskow, & Chobot, 1999). The relationship between the level of speech and competing sound sources is typically quantified by the signal-to-noise ratio (SNR), which represents the level of the speech signal of interest relative to that of competing sounds.

For adults with hearing loss, difficulty understanding speech in the presence of competing sounds (noise) has been reported as a primary reason for dissatisfaction with hearing instruments (Kochkin, 2007). Several strategies exist to improve the performance of hearing instruments when competing background noise is present. These strategies, which will be discussed in further detail later, include: an alternate frequency-gain response to reduce hearing instrument output in some frequencies; directional microphones, which are less sensitive to sound arriving from behind or beside the listener; digital noise reduction (DNR), which uses digital signal processing (DSP) to analyze and remove noise from the output of the hearing instrument (Amlani, 2001; Bentler, 2005; Bentler & Chiou, 2006; Levitt, 2001; Ricketts, 2001, 2005). These noise management strategies are typically available in hearing instruments and can be used alone or in combination with one another.

For children who wear hearing instruments, concerns regarding listening in noise extend beyond satisfaction. Research has shown that children with hearing loss require higher speech levels, higher SNR, and are more susceptible to reverberation than children and adults with normal hearing in order to achieve similar levels of speech recognition performance (Boothroyd, 2004; Elliott, 1979a; Fallon, Trehub, & Schneider, 2000; Fallon, Trehub, & Schneider, 2002; Finitzo-Hieber & Tillman, 1978; Nábělek & Nábělek, 1994; Scollie, 2008; Stelmachowicz, Hoover, Lewis, Kortekaas, & Pittman, 2000). For these reasons, it is especially important to ensure that the level of amplified speech is well above the level of competing noise sources for children with hearing loss who are developing speech and language.

In educational environments, frequency modulation (FM) systems are typically used to overcome the challenges of background noise. These systems use a combination of a transmitter microphone worn by the teacher and a receiver worn by the student (often coupled to a hearing instrument). The transmitter delivers the microphone input directly to the student's receiver. FM systems can effectively improve the SNR by as much as 20dB, which in turn, has been shown to provide significant benefit for understanding speech in the presence of competing noise (Hawkins, 1984; Lewis, Feigin, Karasek, & Stelmachowicz, 1991; Lewis & Eiten, 2004; Lewis, Crandell, Valente, & Horn, 2004; Madell, 1992; Pittman, Lewis, Hoover, & Stelmachowicz, 1999; Thibodeau, 2010).

FM systems are an effective strategy for managing listening in noise within the classroom; however, children have reported many listening situations outside of the classroom, in which listening goals do not practically align with the use of FM systems (Scollie et al., 2010a). Outside the classroom, children with hearing loss typically rely on their hearing instruments alone for listening. Although the noise management strategies introduced above (i.e., frequency-gain shaping, directional microphones, and DNR) are often available in hearing instruments fitted to children, the recommendations regarding the activation or use of these features with children is mixed. Some professional bodies universally recommend directional microphones (King, 2010), others consider them a viable option (CASLPO, Bagatto, Scollie, Hyde, & Seewald, 2010; 2002), while others recommend against use of these features until there is further evidence of effectiveness (AAA, 2003; Foley, Cameron, & Hostler, 2009).

In summary, much literature exists regarding classroom acoustics and the associated implications for listening and learning. The existing literature has identified classroom listening challenges such as speech audibility and recognition when the teacher is the talker, and has addressed these challenges for children with hearing loss through FM technology. However, there is much less literature regarding the listening needs of children in their lives outside traditional classroom instruction.

This chapter begins with an introduction to the background literature on hearing instrument prescription and room acoustics. Next, the concept of non-quiet listening environments and situations is introduced. In this dissertation, “non-quiet” is used to expand our conception of “noise.” Use of the term “noise” in the context of hearing instruments connotes competing signals and may imply high levels of loudness. However, listening situations can involve competing signals without high levels of loudness, and conversely, high levels of loudness can exist independent of unwanted or competing signals (i.e., music). Following the discussion on the types of non-quiet listening situations identified in the extant literature is an introduction to the concept of auditory ecology. This concept was used as a framework for this dissertation, supporting the goal of broadening our efforts to supporting children’s listening in a variety of non-quiet situations. An additional framework provided an overview of the validity requirements of hearing instrument prescription (Scollie, 2004) and is reviewed below. A review of existing noise (non-quiet) management strategies is then provided. Finally, the literature review of this chapter concludes with a discussion about how we may measure the outcomes of such strategies toward the improvement and development of non-quiet listening strategies for children with hearing loss.

1.3 Hearing Instrument Prescription

1.3.1 Linear Hearing Instrument Fitting

Historically, hearing instrument prescription has typically focused on optimizing the frequency-gain response for a single listening situation and input spectrum. Prescriptive algorithms sought to set hearing instruments with linear amplification to theoretical frequency-gain responses designated by the particular prescriptive formula for an average input level of 65 dB SPL. These theoretical optima varied by prescriptive methodology; for example, the National Acoustics Laboratory (NAL) formula sought to maximize speech intelligibility at a most comfortable level (MCL) for the listener, which resulted in loudness equalization across most frequency bands of speech (Byrne, 1986b; Byrne & Dillon, 1986; Dillon, 2001). The Cambridge Formula (CAMFIT) sought to equalize loudness across frequencies, which in turn led to high speech intelligibility as calculated by the Articulation Index (AI) (Moore & Glasberg, 1998; Peters, Moore, Glasberg, & Stone, 2000). The Desired Sensation Level (DSL) method had a specific focus on pediatric hearing instrument use; the formula sought to maximize audibility across frequencies while remaining within the auditory range (above threshold and below level of discomfort) across the amplified frequency range (Dillon, 2001; Gagné, Seewald, Zelisko, & Hudson, 1991a; Gagné, Seewald, Zelisko, & Hudson, 1991b; Seewald et al., 1985).

1.3.2 Non-Linear Advances

The advent of non-linear amplification in hearing instruments led to expanded goals for prescriptive formulae. Algorithms then aimed to provide frequency-gain responses for speech at levels both above and below the average level of speech (e.g. prescriptive targets for speech at a low level such as 50 dB SPL, and a high level of 75 dB SPL)

(Byrne, Dillon, Ching, Katsch, & Keidser, 2001; Cornelisse et al., 1995). For the DSL algorithm, the application of non-linear circuitry allowed for normalization of loudness across a broad range of input levels (Jenstad et al., 2000; Jenstad et al., 1999; Scollie et al., 2005).

Although the various prescriptive methods have evolved in a way that allows for somewhat different listening situations (i.e., a single speech-source at varied levels), the scope of prescriptive formulae may still be considered narrow when compared to the number of listening environments and situations experienced by listeners on a day-to-day basis.

1.4 Room Acoustics

The characteristics of a speech signal and the ability of listeners to understand the speech signal, depend on the acoustic properties of the room in which the signal is presented. There are multiple factors to consider when classifying a room for speech testing, such as: the level of the talker, the level of background noise, 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; Náběĺek & Náběĺek, 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 reverberation time (RT) and decreased SNR (Boothroyd, 2004; Finitzo-Hieber & Tillman, 1978; Náběĺek & Náběĺek, 1994; Nelson & Soli, 2000; Smaldino et al., 2008).

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. RT refers to the length of time required for the level of an emitted sound (at a particular frequency) to decrease by a specified amount after the signal is stopped. For example, RT_{60} refers to the time required for the sound level to decrease by 60 dB. 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; Náběĺek & Náběĺek, 1994; Smaldino et al., 2008).

Measurement of RT_{60} in classrooms has been reported to range from 0.4 sec to 1.2 sec; for comparison, audiometric test booths typically have an RT_{60} of approximately 0.2 sec, living rooms and offices can have an RT_{60} of 0.4 sec to 0.8 sec, while auditoriums and churches can have an RT_{60} greater than 3.0 sec (Náb ělek & Náb ělek, 1994; Smaldino et al., 2008). In general, the ability to understand speech in a room decreases with increasing RT (Náb ělek & Náb ělek, 1994; Smaldino et al., 2008); however, it is important to consider the interaction between reverberation and the distance between talker and listener.

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; Náb ělek & Náb ělek, 1994; Smaldino et al., 2008). Direct sound energy consists of sound waves that travel straight to the listener, without reflecting off of any surfaces in the room. Reflected energy can be divided into two types: i) early reflections, which are sound waves that reach the listener shortly after the direct sound (within approximately 50 msec), and ii) 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 to the source 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 making 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; Náb ělek & Náb ělek, 1994; Smaldino et al., 2008).

Room acoustics play a significant role in speech recognition performance across listeners; however, important considerations must be made for children with hearing loss.

Children with hearing loss require a louder speech signal, higher SNR, and lower RT than their peers with normal hearing (Boothroyd, 2004; Elliott, 1979a; Fallon et al., 2002; Finitzo-Hieber & Tillman, 1978; Nábělek & Nábělek, 1994; Scollie, 2008; Smaldino et al., 2008).

1.5 Non-Quiet Environments

A report by Pearsons, Bennett, and Fidell (1977) described measurements of speech levels across a number of environments. As part of the study, Pearsons et al. (1977) measured speech and background noise levels in 20 classrooms in two different schools. The data indicated that the average background noise levels were 48 and 51 dBA, average speech levels at the front of the classrooms (2 m from source) were 62 and 66 dBA yielding an SNR of approximately +15 dB. Speech levels at the back of the classroom (7 m from source) were approximately 5 dB lower resulting in an SNR of +10 dB. The investigators also mathematically adjusted the levels to predict results at a distance of 1m from the talker. These calculations indicated that teachers' speech levels would increase 1 dB for each dB increase in noise level from 45 to 55 dBA (Olsen, 1998; Pearsons et al., 1977).

A review article by Crandell and Smaldino (2000) reported typical noise levels in classrooms to range from 41 to 51 dBA in unoccupied rooms and levels as high as 67 dBA in occupied classrooms with typical SNRs ranging from -7 to +5 dB. Although differences exist between the summaries of SNRs in classrooms by Pearsons et al. (1977) and Crandell and Smaldino (2000), together the studies report an estimated range of SNR in classrooms of -7 to +15 dB. This range of classroom SNRs suggests that children are often listening below the recommended minimum of +15 dB SNR for educational settings (ANSI, 2009; ASHA, 2005). As discussed above, the effects of reverberation in the room and distance from the talker can impact the sufficiency of a given SNR to facilitate speech understanding.

The broad range of speech levels, noise levels, and SNRs reported for classrooms highlights the importance of FM system use in educational settings. As discussed previously, FM systems can overcome the effects of reverberation, distance, and background noise and can improve SNR by as much as 20 dB (Hawkins, 1984). Combined, these benefits of FM system use can facilitate speech recognition and learning in the more adverse classroom listening conditions listed above.

Additional components of the Pearsons et al. (1977) study included speech and background noise level measurements for a range of environments beyond the classroom; measured environments included suburban and urban homes, department stores, as well as trains and airplanes. A broad range of background noise levels was reported across the various environments measured, noise levels were as low as 45 dBA inside suburban homes and as high as nearly 80 dBA inside trains and airplanes. Measured speech levels also spanned a wide range from 55 dBA inside suburban homes to nearly 80 dBA inside trains and airplanes. This broad range of background noise and speech levels combined to yield an equally broad range of SNRs from -2 to +14 dB. The data reported by Pearsons et al. (1977) illustrate the diverse range of acoustic environments that exist beyond the classroom yet that are just as likely to be experienced by children on a daily basis as classroom environments. Although FM systems serve to counteract the challenges of background noise and low SNR in traditional classroom instruction situations, there is not a clear solution to facilitate listening in the challenging environments and situations children encounter beyond the classroom instruction setting.

1.6 Non-Quiet Listening Needs of Children

A multi-site study was conducted to compare the National Acoustics Laboratory Non-Linear (NAL-NL1) and DSL v4.1 non-linear prescriptive algorithms with 48 children with hearing loss (mean age of 11.4 years) across two sites (Australia and Canada); results are reported across several publications (Ching, Scollie, Dillon, & Seewald, 2010a; Ching et al., 2010b; Ching et al., 2010c; Scollie et al., 2010a; Scollie et al., 2010b). The study incorporated several outcome measures in both objective and self-report domains. Children were assessed with a variety of laboratory outcome measures: a sentence-in-noise task, a consonants-in-quiet task, aided loudness ratings, and paired-comparison judgments. Parent and teacher reports of children's performance were evaluated using the Parents' Evaluation of Aural/oral Performance of Children (PEACH;

Ching & Hill, 2007) and the Teachers' Evaluation of Aural/oral Performance of Children (TEACH) questionnaires. Additionally, the children's own reports were collected with the Self Evaluation of Listening Function (SELF) questionnaire. In the final stages of the study in which children had the ability to switch between the two fitting rationales, they were asked to complete a diary that included three questions about their overall listening impression: i) whether they found the programs to be different; ii) which program they preferred more than 75% of the time; and iii) by how much.

The authors sought to identify relationships of preference among 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, specifically a 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, specifically friends in class, soft speech, sounds from behind, teacher in class, and sounds in the environment (Scollie et al., 2010a).

Ching et al. (2010b) described the electroacoustic properties and differences between fittings for the children in the study across both sites. In general, the DSL fittings provided more gain across frequencies than NAL fittings and the NAL fittings had greater response slopes than DSL fittings. The electroacoustic differences are an important consideration when interpreting the real-life listening preference component of the study in Scollie et al. (2010a). Across sites, children expressed mixed preferences for the two fitting rationales; children at both sites demonstrated a preference for the DSL fitting when listening to lower-level sounds or when they desired louder and clearer output. However, children at both sites also indicated a preference for having access to both fitting rationales as separate programs to be selected depending on a given listening situation. The authors concluded that level, location, and SNR of target sounds are important factors that contributed significantly to children's listening preferences and that children required different amplification characteristics for the varied listening environments they encountered during daily living, perhaps through the prescription and application of a noise program that can be manually selected as needed (Scollie et al., 2010a). An additional and relevant result of this study was the evidence that children in this age range could effectively make use of manually selected listening programs to suit their listening requirements and/or preferences in multiple environments (Scollie et al., 2010a). The authors of this study speculated that children require different amplification characteristics for different environments and that further study of signal processing strategies to manage listening across children's real-world environments may be warranted (Scollie et al., 2010a).

1.7 Auditory Ecology

A large-scale study of adults who wear hearing instruments by Gatehouse, Elberling, and Naylor (1999) and Gatehouse, Naylor, and Elberling (2003, 2006a, 2006b) examined a number of factors that the authors believed may contribute to candidacy for, benefit from, and satisfaction with five different hearing instrument signal processing schemes in real-world listening environments and situations. Auditory ecology was one of the factors investigated, which the authors 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, 2006b). The five signal processing schemes (fit as independent programs) were: two linear fittings and three non-linear fittings, which varied the attack and release times of the low and high-frequency channels of the hearing instrument's compression system.

The authors sought to identify predictor variables by assessing participants' performance with a variety of psychoacoustic and cognitive tasks and measures of auditory ecology, prior to hearing instrument fitting. Psychoacoustic measurements were also conducted in order to assess participants' susceptibility to degraded spectral and temporal information and upward spread of masking.

To examine auditory ecology as a predictor variable for benefit from amplification characteristics, the authors used both a self-report and an objective measure of auditory ecology. The Auditory Lifestyle and Demand Questionnaire (ALDQ; Gatehouse et al.,

1999) was administered to assess the range and importance of listening demands experienced by participants. Objective measurement of the auditory ecology of the participants was conducted using an electronic dosimeter which logged A-weighted Equivalent Continuous Noise Levels (L_{eqA}) from a lapel microphone worn by each participant. The dosimeters were programmed to turn on at 6 am and off at 12 midnight each day for alternate days during a 14-day period which was representative of a “typical two-week period” (Gatehouse et al., 2006b).

Participants completed a diary during each day that the dosimeter was active in order to correlate dosimeter readings with daily activities and situations. In order to calculate the extent to which the acoustic environments of the participants varied, the authors also measured what they referred to as “between-frame variability” and “within-frame variability”. Between-frame variability measurement was performed by calculating the difference between the mean L_{eqA} values across defined time-frames. Within-frame variability was measured by calculating the standard deviation around the mean of a defined time-frame.

The study incorporated several outcome measures which assessed auditory, self-report, and objective environmental aspects of the participants’ experiences. Speech intelligibility was measured using the Four Alternative Auditory Feature test (FAAF; Foster & Haggard, 1987) which required the listener to identify target words presented with competing noise. Subjective measurements of listeners’ experiences were assessed using a number of self-report measures completed in paper and pencil format. The Abbreviated Profile of Hearing Aid Benefit (APHAB; Cox & Alexander, 1995) was used to assesses benefit from the hearing instruments with each memory. The Satisfaction with Amplification in Daily Life (SADL; Cox & Alexander, 1999) questionnaire was completed in order to assess aspects of satisfaction. The Glasgow Hearing Aid Benefit Profile (GHABP; Gatehouse, 1999) was also administered to assess hearing instrument use, benefit, and satisfaction across pre-specified and individual-specified situations. In addition to the three established self-report scales, a novel questionnaire called the Hearing Aid Performance Questionnaire (HAPQ; Gatehouse et al., 2006a) was piloted and developed with the specific goal of differentiating between linear and non-linear hearing instrument fittings (Gatehouse et al., 2006b).

Gatehouse et al. (2006b) reported the impact of auditory ecology on candidacy for hearing instrument fitting for the participants in the study. The data were reported as correlations between benefit factors and predictor factors for each of the hearing instrument fittings. The benefit factors were; i) listening comfort, ii) satisfaction, iii) reported intelligibility, and iv) objective speech recognition. There were four predictor factors that pertained to auditory ecology; i) Auditory Lifestyle and Demand (ALD), which emerged as a single factor after data reduction; ii) Overall Dosimeter Distribution, which was associated with parameters of the overall distribution of the collected dosimeter data; iii) Dosimeter Within-Frame Variability, as described previously; iv) Dosimeter Between-Frame Variability, as described previously.

The correlations between benefit and predictor variables indicated differential benefit between hearing instrument fittings related to the participants' auditory ecology. Results for the two linear fittings indicated negative correlations between the ALD and dosimeter predictors for all three self-report benefit factors, indicating that participants with more restricted auditory ecology showed greater benefit from a linear fitting. Results for the three non-linear fittings indicated positive correlations between the ALD predictor factor and the three self-report benefit factors, which indicated that participants who reported a greater range of auditory ecology reported greater benefit from any of the three non-linear fittings.

Although there was benefit from all three non-linear fittings for participants with greater ranges of auditory ecology, there was greater benefit with slow-acting compression for participants with greater Dosimeter Between-Frame Variability and greater benefit from fast-acting compression for participants with greater Dosimeter Within-Frame Variability.

The differential results between the two linear and three non-linear fittings provide support for the assumed goals of the non-linear fitting rationales. Non-linear fittings are typically thought to provide increased comfort and audibility relative to linear fittings

(Ching, Hill, van Wanrooy, & Agung, 2004; Dillon, 2001; Jenstad et al., 2000; Jenstad et al., 1999), which is reflected in the self-reported benefit factors above. The different goals of slow- versus fast-acting compression systems are also reflected in the dataset. Fast-acting compression systems attempt to overcome some of the impediments imposed by sensory-neural hearing loss by maximizing the moment-to-moment audibility of a speech signal; thus, the hearing instrument must act rapidly over periods of time comparable to the rapid fluctuations in a speech signal (Gatehouse et al., 2006a). Slow-acting compression systems are designed to provide audibility with minimal processing and distortion artifacts while adapting to the longer-term changes in a listener's auditory environment, or as listeners move from one listening situation to the next (Gatehouse et al., 2006a). If the Dosimeter Between-Frame Variability predictor was considered to be an indicator of the extent to which a listener's auditory environments differed from each other, and the Dosimeter Within-Frame Variability predictor was an indicator of the extent to which a specific auditory environment changed, then the above goals of the contrasted compression implementations appear to be supported by the Gatehouse et al. (2006b) data.

1.7.1 Application to Pediatric Fitting

Given the importance of auditory ecology as a predictor for hearing instrument benefit in adult subjects, it is likely to be an important consideration in the realm of pediatric hearing instrument prescription as well. As shown in the Gatehouse et al. (1999; 2003; 2006a; 2006b) study, adults experienced variation in their auditory ecologies large enough to warrant consideration during the hearing instrument fitting process. As was discussed previously, children experience a broad range of acoustic environments and situations. Since children are likely to experience just as much, if not more variation in their day to day listening environments and situations than adults, it seems plausible that auditory ecology should also be considered in pediatric audiology.

1.8 Considering Auditory Ecology to Improve Validity of Hearing Instrument Prescription

Scollie (2004) aimed to apply the concept of validity to prescriptive algorithms. The following four types of validity were defined and applied to hearing instrument prescription: i) content validity, ii) concurrent validity, iii) predictive validity, and iv) construct validity. Within the scope of the current paper, the concepts of content, predictive, and construct validity are most relevant with regard to auditory ecology. Scollie (2004) defined content validity in terms of the comprehensiveness of a prescription and whether it accounts for all psychoacoustic and electroacoustic variables that impact hearing instrument fitting outcomes. An individual's auditory ecology has been demonstrated to impact hearing instrument fitting outcomes and benefit; it follows that consideration of listeners' auditory ecology as part of the prescriptive process would improve the content validity of a prescription.

Predictive validity was discussed in terms of hearing instrument wearers receiving more benefit from an instrument fitted with a prescription than with a hearing instrument fitted without such a prescription (Scollie, 2004). Auditory ecology has been shown to have a direct relationship with hearing instrument benefit; thus, it is plausible that a prescription that considers a listener's auditory ecology may provide more benefit than a prescription that does not, which in turn may increase the predictive validity of the prescription process.

The concept of construct validity as it relates to hearing instrument prescription was described as whether or not the prescription provides an "accurate, comprehensive, electroacoustic prescription of a theoretically optimal hearing aid" (Scollie, 2004, p. 100). If the concept of a theoretically optimal hearing instrument is expanded to include providing benefit across all environments and situations encountered by the wearer, then the inclusion of auditory ecology as part of the prescription could therefore add to the construct validity of the prescription.

1.9 Hearing Instrument Prescriptive and Processing Strategies for Non-Quiet Environments

As discussed previously, hearing instrument prescriptive algorithms generally prescribe a theoretically derived frequency-gain response, which has been developed for listening to a speech source in a quiet environment (Byrne, 1986a, 1986b; Byrne et al., 2001; Cornelisse et al., 1995; Dillon, 2001; Gagné et al., 1991a; Gagné et al., 1991b; Moore & Glasberg, 1998; Moore, Glasberg, & Stone, 1999; Peters et al., 2000; Scollie et al., 2005; Seewald et al., 1985). However, the literature has demonstrated that real-world listening conditions generally involve sound sources in addition to a single speech source and that typical environments are generally non-quiet (Kochkin, 2007, 2010; Olsen, 1998; Pearsons et al., 1977; Scollie et al., 2010a). A number of strategies exist to assist individuals who wear hearing instruments to manage listening in non-quiet environments. Alternative frequency-gain responses, directional microphones, and DNR are three commonly employed strategies used to facilitate non-quiet listening. These strategies are defined here briefly, with a more extensive overview detailed in the chapter corresponding with the study of each strategy. Specifically, an alternate frequency-gain response (DSL v5 Noise prescription) is explained in Chapter 3, and directional microphones and DNR in Chapter 4.

1.9.1 DSL v5 Noise Prescription

The most recent version of DSL (version 5) includes a prescription for use in noise. Briefly, the DSL v5 Noise prescription uses an alternate frequency-gain response designed for use as an additional hearing instrument memory to manage comfort in noisy environments (Scollie et al., 2005). Essentially, relative to the DSL v5 Quiet prescription, the frequency-gain shaping reduces low and high frequency gain and maintains gain for frequencies thought to be important to speech recognition.

1.9.2 Directional Microphones

Directional microphones are less sensitive to sounds originating from certain (non-frontal) directions relative to omni-directional microphones (Ricketts, 2000a, 2001, 2005). Directional microphones in hearing instruments have been shown to improve speech recognition in noise for adults (Amlani, 2001; Bentler, Egge, Tubbs, Dittberner, & Flamme, 2004; Bentler, Palmer, & Dittberner, 2004; Bentler, Palmer, & Mueller, 2006; Bentler, Tubbs, Egge, Flamme, & Dittberner, 2004; Gnewikow, Ricketts, Bratt, & Mutchler, 2009; Hornsby & Ricketts, 2007; Ricketts, 2000b, 2001, 2005; Walden, Surr, Cord, & Dyrlund, 2004; Walden et al., 2005) and children (Gravel, Fausel, Liskow, & Chobot, 1999; Kuk, Kollofski, Brown, Melum, & Rosenthal, 1999; Ng, Meston, Scollie, & Seewald, 2011; Ricketts et al., 2007).

1.9.3 Digital Noise Reduction

DNR is a DSP feature available in many modern hearing instruments. DNR algorithms analyze sound picked up by the hearing instrument microphone(s) in order to detect and reduce noise in the hearing instrument's output. A variety of approaches to DNR exist in commercial hearing instruments all of which generally share two common goals. The primary goal is improvement of speech recognition in noise and a secondary goal is improving listening comfort in noisy situations (Bentler & Chiou, 2006; Levitt, 2001). While there is minimal evidence to suggest that fast-acting DNR systems can improve speech recognition in steady state noise (Galster & Ricketts, 2004), in general, DNR processing has shown little effect in achieving the primary goal of improving speech intelligibility in the presence of noise (Alcántara, Moore, Kühnel, & Launer, 2003; Bentler & Chiou, 2006; Bentler, Wu, Kettel, & Hurtig, 2008; Mueller, Weber, & Hornsby, 2006; Ricketts & Hornsby, 2005; Sarampalis, Kalluri, Edwards, & Hafter, 2009) and in some cases has resulted in decrements in speech recognition performance (Jamieson, Brennan, & Cornelisse, 1995; Sarampalis et al., 2009; Van Tasell, Larsen, & Fabry, 1988). However, research has demonstrated a general ability of DNR processing to achieve the secondary goal of improved listening comfort (Bentler & Chiou, 2006; Mueller et al., 2006; Palmer, Bentler, & Mueller, 2006; Ricketts & Hornsby, 2005) and reducing listening effort (Sarampalis et al., 2009). Studies of children's performance with DNR has demonstrated similar results to those of adults, indicating no significant difference in speech intelligibility with DNR use (Pittman, 2011; Stelmachowicz et al., 2010). Currently, there is little evidence regarding effects of DNR on children's listening comfort or loudness perception reported in the literature.

1.10 Outcome Measurement

Evaluation of individuals' performance with and benefit from hearing instruments is typically conducted with behavioural outcome measurement (Humes, 1999). Non-quiet listening situations can generally be divided into two general categories with accompanying goals for hearing instruments; i) speech amidst background noise, a situation in which understanding speech is the primary goal, and ii) loud environments, a situation in which comfort or tolerance is the primary goal. In this research, three domains of outcome measurement with children were of particular interest: consonant recognition in quiet, sentence recognition in noise, and loudness perception. Together, these outcome measures allowed evaluation of both speech understanding and comfort at high and low levels and high and low SNRs.

The following four psychometric considerations for hearing instrument outcome measurement require attention. First, the sensitivity of the measure must be considered, which means we must consider whether the measure will detect differences between interventions or conditions. Second, the measure should meet the requirements of both construct and external validity. That is, the measure fulfils the intended goal of measurement and the measure's results can be related to real-world performance, respectively (Portney & Watkins, 2000b). Third, the reliability of the measure should ensure reproducible results. That is, reliability considers the consistency with which an instrument measures a variable (Portney & Watkins, 2000a). Fourth, feasibility and brevity must be considered. These criteria lend to the ability of clinicians and researchers to effectively and efficiently (realistically) make use of the measure (Cheesman & Jamieson, 1996; Feeney & Franks, 1982). In attempts to satisfy the first three criteria above, the fourth criterion can pose a challenge. For example, in optimizing reliability, test time must usually increase; participant fatigue may then lead to reduced reliability. Thus, a balance must be achieved in selecting outcome measures. In this work, the goal of representing real-world listening was a priority, given that we already know that directional microphones and DNR are *efficacious* (Palmer, 2007) for the goals of improved speech recognition and comfort in noise, respectively. However, determining *effectiveness* (Palmer, 2007) for children in non-laboratory settings, such as the schools in which they spend much of their daily lives, was a goal of this research. This step is necessary if we are to begin recommending the use of noise management strategies in children's hearing instrument fittings. For these reasons, the goals of optimal external validity and feasibility were prioritized in study design.

The psychometric properties above and the conceptual framework of auditory ecology, and Scollie's (2004) considerations for validity of a hearing instrument fitting strategy informed the selection of outcome measures used in this body of work. That is, the measures used to evaluate effectiveness of noise management strategies should be sensitive to the goals of pediatric hearing instrument fitting (audibility, speech recognition, and comfort), while aligning with the types of real-world situations in which they would be used. The following section details the attempt to select sensitive and valid outcome measurement tools to facilitate the meaningful evaluation of children's outcomes with hearing instrument fitting strategies for non-quiet listening situations. Reliability and feasibility were also important factors in selecting the measures for this research.

1.10.1 Speech Recognition Testing

Numerous tests have been designed to measure speech recognition ability. The available tests generally differ in terms of stimulus materials used, presentation SNR, and response format. Two aspects of a given speech recognition test contribute to stimulus recognition. First, the acoustic characteristics of the target stimulus itself and second, the context in which the target stimulus is presented (Boothroyd, 1968; Boothroyd & Nittrouer, 1988; Elliott, 1979b; Nittrouer & Boothroyd, 1990). The acoustic characteristics of the target stimulus determine audibility. However, with context, some listeners may be able to recognize the stimulus even without full stimulus audibility. Two types of context are generally thought to be of importance: phoneme within-word context and word within-sentence context as both of these relate to predictability of the stimulus, and thus score on the test. Due to the confounding effects of acoustic characteristics and contextual information, a test battery approach to speech recognition testing has been suggested (Cheesman & Jamieson, 1996; Stelmachowicz, 1999).

With children, it can be difficult to separate factors such as auditory experience, education, and phonological development from true hearing ability (Boothroyd, 1997; Hnath-Chisolm, Laipply, & Boothroyd, 1998; Stelmachowicz, 1999). It is important to evaluate the audibility of acoustic information that is important for speech and language development because this is the primary goal of pediatric hearing instrument fitting (Scollie et al., 2005; Seewald et al., 1985; Stelmachowicz et al., 2007; Stelmachowicz et al., 2004). For the purposes of hearing instrument outcome measurement, a speech recognition test should be more sensitive to variations in audibility than to other factors such as auditory experience, education, and phonological development (Hnath-Chisolm et al., 1998).

Response format (open-set versus closed-set) is also a factor that may impact speech recognition test validity by introducing demands beyond audibility. Open-set tests do not constrain responses with a list or display of response options, so the participant must produce the response orally (or in written form). For the purposes of consonant recognition testing, an open-set test was thought to compromise the validity of scoring. Due to the association between hearing loss and speech articulation challenges, the researcher may not be able to discriminate between some speech sounds produced by children with hearing loss, thus comprising scoring for the test (Kirk, Diefendorf, Pisoni, & Robbins, 1997). Additionally, scores with an open-set test format may be more impacted by cognitive factors, than scores with a closed-set test (Clopper, Pisoni, & Tierney, 2006; Sommers, Kirk, & Pisoni, 1997). For these reasons, the University of Western Ontario Distinctive Features Differences test (UWO-DFD; 1996) was chosen for this work. Details of this test are discussed in the following section.

1.10.2 Consonant Recognition

Perception of spoken language is a primary goal of hearing instrument fittings and hearing instrument technology. Assessment of language perception is a critical component of hearing instrument evaluation, which can assist in determining the appropriateness of a given instrument or fitting. In the pediatric population, evaluation of speech recognition performance is essential to ensure that hearing instruments facilitate language acquisition and development. Consonant recognition in quiet is of interest because alternate frequency-gain responses have the potential to affect aided speech recognition (Scollie et al., 2010b; Stelmachowicz et al., 2000; Stelmachowicz et al., 2004). Consonants provide the basis for understanding what was said, and tend to be higher in frequency and lower in level than vowels (ANSI S3.5, 1997). Hearing instrument prescriptive algorithms, such as DSL v5, aim to optimize, through frequency-gain response shaping, the audibility of these important speech sounds. However, the DSL v5 Noise prescription reduces prescribed gain relative to the DSL v5 Quiet prescription frequency-gain response. No experimental data evaluating the impact of this change on speech recognition has been reported to date. Therefore the comparative measurement of consonant recognition with these alternate prescriptions was a goal of the present work.

Feeney and Franks (1982) developed the Distinctive Features Differences test (DFD) which was a closed-set consonant recognition task incorporating 13 target consonants found to be frequently confused by listeners with hearing loss. The test was designed to be scored based on distinctive feature confusions rather than entire phoneme recognition, which the authors reported to increased reliability of the test (Feeney & Franks, 1982).

Based on the work of Feeney and Franks (1982), Cheesman and Jamieson (1996) developed a nonsense word test called the University of Western Ontario Distinctive Features Differences test (UWO-DFD) that provided a general measure of consonant identification ability and indicated the types of confusion errors made by listeners. The UWO-DFD maintained the nonsense word format (/λ**C**IL/) of the original DFD test, but increased the number of target consonants to 21 (C = **b, ch, d, f, g, h, j, k, l, m, n, o, p, r, s, sh, t, th, v, w, y,** and **z)**. This increased number of consonant sounds allowed for a broader range of potential errors and confusions that could occur. The UWO-DFD used four talkers (two male, two female), which the authors reported to increase the generalizability of the test by including a range of voices and speaking styles.

The UWO-DFD has been used as a speech recognition measure in a variety of research applications focused on pediatric hearing instrument evaluation. These studies have shown the test to be sensitive to differences in age and hearing loss (Scollie, 2008), differences in hearing instrument frequency-gain response (Glista et al., 2009; Scollie et al., 2010b), and the interaction of test level and linear versus nonlinear hearing instrument processing (Jenstad et al., 1999). Through development and continued use, the UWO-DFD has demonstrated sensitivity and high reliability across children and adults with normal hearing and hearing loss. For these reasons, the UWO-DFD was selected to measure the effect of the DSL v5 Noise prescription on consonant recognition relative to the DSL v5 Quiet prescription in this work. Specifically, we aimed to determine if consonant recognition was compromised by the frequency-gain response adjustments imposed by the DSL v5 Noise prescription. These data are presented in Chapter 3 of this dissertation.

1.10.3 Speech Recognition in Noise

As previously stated, speech recognition in noise is a primary source of complaint in adult hearing instrument wearers (Kochkin, 2007). Given the dynamic auditory ecology of children (Olsen, 1998; Pearsons et al., 1977; Scollie et al., 2010a) and their need for greater SNR than adults, a measure of speech recognition in noise was required for the present work. Words presented in sentences have been developed for pediatric speech recognition testing (Bench, Kowal, & Bamford, 1979; Kirk et al., 1997). Sentences represent the natural dynamics of spoken language, and permit use of contextual cues, thus supporting the goal of using externally valid stimuli to assess effectiveness of noise management strategies while assisting speech recognition under adverse listening conditions. Additional goals in the selection of the speech recognition in noise measure included; i) externally valid competing signal (realistic noise source), ii) age appropriate task, iii) sensitivity, iv) reliability, and v) feasibility/brevity.

1.10.3.1 Competing Noise

The competing or background noise used in commercially available speech-in-noise tests typically consists of either constant-level speech spectrum noise or multi-talker babble (consisting of either four or six talkers in the presently discussed tests). Constant-level background noise is not representative of the environment encountered by most people in their everyday situations, whereas multi-talker babble is the most common environmental noise encountered by listeners in everyday life (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004; Wilson, 2003). Fikret-Pasa (1993) measured and compared the intensity variations of the background noise found in everyday situations (e.g., shopping malls and restaurants) with those of commercially available noise maskers (speech-spectrum noise and multi-talker babble). She found that real-world background noise contained level variations of 2.8 to 8.4 dB, while speech-spectrum noise maskers contained almost no variation in level. Fikret-Pasa (1993) examined a number of multi-talker babble noises: Villchur two-talker babble; Auditec four-talker babble (Auditec of St. Louis, 1971); Maryland babble (Sperry, Wiley, & Chial, 1997); and the Speech Perception in Noise (SPIN) twelve-talker babble (Kalikow, Stevens, & Elliott, 1977). Of these, she found the Auditec four-talker babble to have the greatest degree of level variation (Fikret-Pasa, 1993). Four-talker babble is thought to represent a realistic social gathering in which a listener may selectively listen to any of a number of talkers (Killion et al., 2004; Wilson, 2003). Constant-level noise maskers eliminate the temporary gaps in the background noise, which are present in the speech streams of real talkers and therefore likely incorporate only energetic masking effects on the listener. In contrast, multi-talker babble is composed of individual speech streams, contains the temporal and spectral characteristics of speech, may contain semantic information, and thus likely imposes both informational and energetic masking effects.

1.10.3.2 Speech Stimuli

The Bamford-Kowal-Bench Speech-in-Noise Test (BKB-SIN; Niquette, 2003) uses Americanized BKB sentences (first-grade reading level) recorded by a male talker, amidst competing Auditec four-talker babble (Auditec of St. Louis, 1971). Listeners are presented with sentences at varying SNR, which are scored for correct repetition of three to four key words within each sentence. The BKB-SIN uses a descending presentation SNR (method of constants) to assess listener performance. Stimuli are pre-recorded with the level of the target sentence fixed across sentences while the level of the four-talker babble is increased (to reduce SNR) as the test progresses (Etymotic Research, 2005). Data on list equivalence was obtained from groups of adults and children with normal hearing and a group of cochlear implant participants. The data from the equivalence evaluation were then used to develop equivalent list pairs. To balance the difficulty between list pairs, the most difficult lists were paired with the easiest lists, and the more equivalent lists were paired together (Etymotic Research, 2005).

1.10.3.3 Sensitivity, Reliability, and Feasibility

The BKB-SIN has been used as an outcome measure for hearing instrument features (Ng et al., 2011), and in cochlear implants (Donaldson et al., 2009; Litovsky, Parkinson, Arcaroli, & Sammeth, 2006). Ng et al. (2011) found that the BKB-SIN was sensitive to the effects of directional microphones on speech recognition in noise for children who use hearing instruments. Litovsky et al. (2006) found the BKB-SIN was sensitive to bilateral versus unilateral listening, and Donaldson et al. (2009) found that the BKB-SIN was predictive of real-world, self-assessed listening benefit. Two of the studies included listeners with normal hearing and demonstrated the BKB-SIN's sensitivity to differences between groups (Donaldson et al., 2009; Ng et al., 2011).

According to the test developers, the BKB-SIN can be reliably administered within a feasible timeframe (Etymotic Research, 2005; Niquette, 2003). The test manual provides age-specific 95% confidence intervals for test-retest reliability, across a range of total number of stimulus sets (list pairs) (Etymotic Research, 2005). In an adapted use of the BKB-SIN as a pediatric aided outcome measure, Ng et al. (2011) confirmed that most participants' test-retest change fell within the published limits.

In comparison with other commercially available tests of speech in noise recognition, the BKB-SIN is considered to be a test with high validity, reliability and sensitivity (Schafer, 2010). The BKB-SIN is a deterministic rather than an adaptive procedure, which may cause less participant frustration as compared to tests which adapt to the level of 50% correct (Wilson, McArdle, & Smith, 2007). The test materials have been suggested as being more appropriate for use with children or individuals with profound hearing loss than other available speech-in-noise tests (Schafer, 2010; Wilson et al., 2007). Additionally, the CD-based format of the BKB-SIN test facilitates classroom testing (Schafer, 2010). Finally, the administration time of each list pair of the BKB-SIN is three minutes, which permits feasible and practical outcome measurement (Etymotic Research, 2005).

1.10.4 Summary of Speech Recognition Test Battery

A closed-set, low-context task for consonant recognition was chosen for use in the study described in Chapter 3. This task was deemed appropriate for the purpose of determining whether or not the DSL v 5 Noise prescription compromised speech recognition abilities. The words in sentences in noise task used in the studies, described in Chapters 3 and 4, was chosen for the following reasons. A words-in-sentences task is considered representative of real-world speech (Villchur, 1982). Similarly, the noise used in the BKB-SIN has been deemed the most representative of real-world situations (Fikret-Pasa, 1993), and this study sought to have a high level of external validity. A feasible number of list pairs from this test can be used with good reliability and the test has been shown to be sensitive to differences in noise management strategies. Finally, the brief and deterministic procedure was thought to be especially important for a test battery approach, to reduce participant frustration through multiple test sessions. This test battery was thought to be the best fit to the combined needs of psychometrically sound speech recognition measurement and the goals of the research.

1.10.5 Loudness Perception

Loudness discomfort has been suggested as a leading cause of hearing instrument rejection or dissatisfaction (Hawkins, Walden, Montgomery, & Prosek, 1987; Kochkin, 2007). For this reason, an assessment of loudness perception appears to be an important aspect of hearing instrument outcome measurement. Restoration of normal loudness perception is viewed as a fitting goal that extends across the various hearing instrument prescriptive methods (Byrne et al., 2001; Cornelisse et al., 1995; Cox & Gray, 2001; Moore, 2000). In this context, normal loudness refers to the perceived loudness of sounds at the same level being approximately equal for hearing instrument users and listeners with normal hearing. Specifically, soft environmental sounds should be audible, but reported as “soft” while wearing hearing instruments, average sounds should be reported as comfortable after fitting, and loud sounds should be reported as loud, but not uncomfortable, with hearing instruments (Cox & Gray, 2001).

The Contour Test of Loudness (Cox, Alexander, Taylor, & Gray, 1997) yields a level for each of seven categories of loudness ranging from "very soft" to "uncomfortably loud". The test begins stimulus presentation at 5-10 dB above threshold and then ascends in two or five dB steps (depending on hearing thresholds) until the "uncomfortably loud" level is reached.

Three or four ascending runs are performed and the median of all levels assigned to a given category reported as the final level. Cox et al. (1997) report normative data for the Contour Test of Loudness as well as the reliability of the procedure. The authors described the Contour Test of Loudness as a clinically viable measure with reliability similar to that of audiometric threshold testing (Cox et al., 1997). The original test was modified by Cox and Gray (2001) to allow for stimulus presentation in sound field instead of earphones as a method of verifying loudness after hearing instrument fitting. While there is literature regarding loudness perception of speech using the Contour Test of Loudness or similar procedures (Ching et al., 2004; Cox & Gray, 2001; Jenstad et al., 2000; Jenstad et al., 1999; Scollie et al., 2010b), studies have typically used speech in quiet. There is less information available regarding the effect of competing noise in loudness perception.

An adaption of the Contour Test of Loudness was used in the studies reported in Chapters 3 and 4. For the same reasons as described in Sections 1.10.3.1 and 1.10.3.2, the BKB-SIN sentences and Auditec four-talker babble were used in this loudness perception task. The stimuli for this task were thus representative of real-world listening, and specifically addressed the research goals of evaluating loudness perception for both speech alone and speech in the presence of competing sound sources.

1.11 Rationale for Current Study

Modern hearing instruments offer three main options to manage non-quiet listening: frequency-gain shaping, directional microphones, DNR, and the combinations of these technologies. These options are regularly employed in adult hearing instrument fittings (Johnson, 2008; Kirkwood, 2006; Kochkin, 2005).

Current pediatric audiology best practices do not uniformly address options for improving speech recognition or loudness perception in non-quiet situations (AAA, 2003; CASLPO, 2002; Foley et al., 2009; King, 2010). The current American guideline cautions against the use of noise management in pediatric hearing instrument fittings pending supportive research evidence; yet, children have demonstrated a desire for non-quiet amplification options as well as the ability to manually select listening programs (Scollie et al., 2010a). Although recommendations exist for the use of additional hearing instrument memories (manually accessible listening programs) for telephone use or in the case of a child with fluctuating hearing loss (AAA, 2003), no guideline currently exists for the use of additional or alternate memories for use in non-quiet environments and situations.

For these reasons, an evaluation of children's speech recognition and loudness perception with available non-quiet management options is warranted. A preliminary study was conducted to explore the school-age listening landscape, because auditory ecology is an important factor in developing valid approaches to hearing instrument fitting and there were gaps in knowledge relating to children's daily listening needs. The existing literature regarding children's listening needs has focused primarily on classroom acoustics, with the teacher's voice as the target signal of interest. It seems that a gap exists in understanding the listening needs of children in their daily routines when their listening needs diverge from listening to lessons and instructions spoken by a teacher. As a precursor to the investigation of management options for non-quiet listening, a first step to fill this gap in knowledge was necessary, and is presented in Chapter 2.

1.12 Presentation Outline

This chapter has reviewed the relevant background theoretical and empirical literature that informed this work, including existing knowledge about hearing instrument prescriptions, room acoustics, non-quiet listening situations, auditory ecology, validity of hearing instrument prescriptions, existing non-quiet hearing instrument strategies, and finally outcome measurement.

In Chapter 2, I present an exploration of the listening environments and situations encountered by the participants in the remainder of this research. These environments and situations were studied in an elementary school and a high school. These sites were regular public schools serving children with and without hearing loss. A daycare was also included in this preliminary study in order to extend the exploration of children's auditory ecology into the pre-school age range. The overall purpose of this work was to illustrate the auditory ecology of children during school day, in both instructional and non-instructional times. The research questions addressed in Chapter 2 are: i) What are the reverberation times across settings within the school or daycare? ii) What is the spectral shape of signals that children experience? iii) What are typical noise and sound levels and sources in various school settings throughout a school day?

In Chapter 3, I present a study comparing outcomes with DSL v5 Quiet and Noise prescriptions. The research questions addressed in Chapter 3 are: i) Does use of the two prescriptions result in differences in consonant recognition? ii) Does use of the two prescriptions result in a difference in sentence recognition in noise performance? iii) Does use of the two prescriptions result in different comfort ratings for loud sounds? The experimental design of the study presented Chapter 3 is summarized in Appendix A.

In Chapter 4, I present a study comparing outcomes with each of the three noise management strategies discussed in this chapter and combinations of these strategies. The research questions addressed in Chapter 4 are: ii) Does the use of a prescribed frequency-gain response, directional microphone, DNR, or a combination result in better speech-in-noise recognition? ii) Does the use of a prescribed frequency-gain response, directional microphones, DNR, or a combination result in differences in comfort ratings for loud sounds? The experimental design of the study presented in Chapter 4 is summarized in Appendix B.

Finally, a general discussion is presented in Chapter 5, including collective implications of the research described in Chapters 2 to 4. The collective results of these three related studies may inform the eventual development of best practice guidelines for the management of non-quiet listening for children with hearing loss. Strengths and limitations of this research are discussed and suggested steps toward development of a non-quiet listening strategy are explored, including recommendations for future research.

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Chapter 2

2 An Exploration of Non-Quiet Listening at School

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 was a precursor to the investigation of hearing instrument fitting strategies for non-quiet listening environments and situations presented in Chapters 3 and 4.

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 (Auriemmo 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; Foley, Cameron, & Hostler, 2009), others consider them viable options (Bagatto, Scollie, Hyde, & Seewald, 2010; CASLPO, 2002), and others 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 needs 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, 2006b), 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 environments in which children spend their days. 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 inform 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.

2.1 Auditory Ecology: Children in Non-Quiet Environments

As discussed in Chapter 1, 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, 2006b). A hearing instrument’s ability to support multi-environment listening is a significant predictor of hearing instrument benefit in adults (Hickson, Clutterbuck, & Khan; Kochkin, 2005). A recent study of hearing instrument outcome in children suggests that multi-environment listening is also important for children. This 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, 2010a; Ching et al., 2010b; Ching et al., 2010c; 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 relationship between prescription preferences across 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 loaded onto 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 at school. Although this was not primarily a study of classroom acoustics per se, traditional measures of room acoustics were included to allow description of the children's classrooms, and are defined below.

2.2 Room Acoustics: Brief Review

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 the talker, the level of background noise, 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 (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).

In order to be understood clearly, the level of speech in a given environment must be sufficiently above the level of background noise. SNRs encountered in classrooms can range from -7 to +15 dB (Crandell & Smaldino, 2000; Olsen, 1998; Pearsons, Bennett, & Fidell, 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; Finitzo-Hieber & Tillman, 1978; Nábělek & Nábělek, 1994; Smaldino et al., 2008). Measurement of RT_{60} in classrooms has been reported to range from 0.4 sec to 1.2 sec; for comparison, audiometric test booths typically have an RT_{60} of approximately 0.2 sec, living rooms and offices can have an RT_{60} of 0.4 sec to 0.8 sec, while auditoriums and churches can have an RT_{60} greater than 3.0 sec (Nábělek & Nábělek, 1994; Smaldino et al., 2008). In general, the ability to understand speech in a room decreases with increasing RT (Finitzo-Hieber & Tillman, 1978; Nábělek & Nábělek, 1994; Smaldino et al., 2008); however, it is important to consider the interaction between reverberation and the distance between talker and listener.

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 of any surfaces in the room. Reflected energy can be divided into two types i) early reflections, which are sound waves that reach the listener shortly after the direct sound (approximately 50 msec), and ii) 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 making 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 0.6 sec for classrooms with an enclosed volume of less than 283 m^3 (10 000 ft^3); for larger classrooms, the background noise level recommendation remains at 35 dBA with the recommended maximum RT_{60} increased 0.7 sec. 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 failed 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; Finitzo-Hieber & Tillman, 1978; Nábělek & Nábělek, 1994; Neuman, Wroblewski, Hajicek, & Rubinstein, 2010; Scollie, 2008; Smaldino et al., 2008). As discussed in Chapter 1, a wireless microphone can be worn by the teacher to enhance speech understanding during instruction. 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 both 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 is needed, which extends beyond the existing literature on classroom acoustics.

2.3 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. Specifically, this study sought to address the following questions with regard to the acoustic settings and situations experienced by the participants: 1) What are the reverberation times (RT_{60}) across settings within the school or daycare, 2) What is the spectral shape of signals that children experience, and 3) What are typical noise and sound levels and sources across various school settings throughout a day? These measurements are also compared to those reported in the literature of larger-scale classroom acoustics, in order to determine the representativeness of the chosen sites of study.

2.4 Methods

2.4.1 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 centre. The school sites included an elementary school (kindergarten to grade eight, ages 5 to 14 years old) and a high school (grades 9 to 12, ages 13 to 18 years old) 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 participate in a future study of hearing instrument fitting for non-quiet environments. The third site, a daycare (ages three months to five years), was chosen to broaden the range of ages and environment types included.

2.4.2 Procedures

2.4.2.1 Unoccupied Room Measurements

The study began with acoustic measurements across the school and classroom environments encountered by students on a daily basis; these measurements were made 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). An AKG C4000B condenser microphone (1-inch dual-diaphragm condenser transducer with a selected omnidirectional polar pattern) was used for recording with a powered speaker (Simeon 500WU) used for stimulus presentation in the RT_{60} estimates.

Noise floor measurements were performed by positioning the recording microphone in the centre 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 centre 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 2-1 summarizes general characteristics of the various rooms across the three sites including whether rooms had carpet or tiles, had windows with or without curtains, and active ventilation systems.

2.4.2.2 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 20 Hz to 20,000 Hz. The portable 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: “quiet”, when there was no audible background noise or an overall level below 50 dBA; “speech alone”, when there was a single primary talker amidst no audible background noise; “speech in noise”, when there was a speech signal of interest (from one or more talkers) amidst audible background noise; 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 system 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.

Table 2-1: 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

2.5 Results

2.5.1 Reverberation Time across School-Day Settings

Reverberation time (RT_{60}) data show a wide range of values across all three sites (Figure 2-1). In general, core learning areas such as classrooms, computer rooms, and hearing resource rooms demonstrated RT_{60} of under 0.6 sec. This indicates that the primary instructional environments in the schools measured were in compliance with ANSI recommendations. Gymnasia demonstrated large RT_{60} values of over 1.0 sec at all three 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 gymnasia and hallways are not considered "core learning areas" and therefore are not within the scope of the ANSI Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools (ANSI S12.60, 2010) recommendations.

2.5.2 Spectral Characteristics across School-Day Settings and Situations

Spectral data from classrooms at all three sites show a broad range in level (Figure 2-2). 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 present in the high school classroom, which remained active for most of the school day.

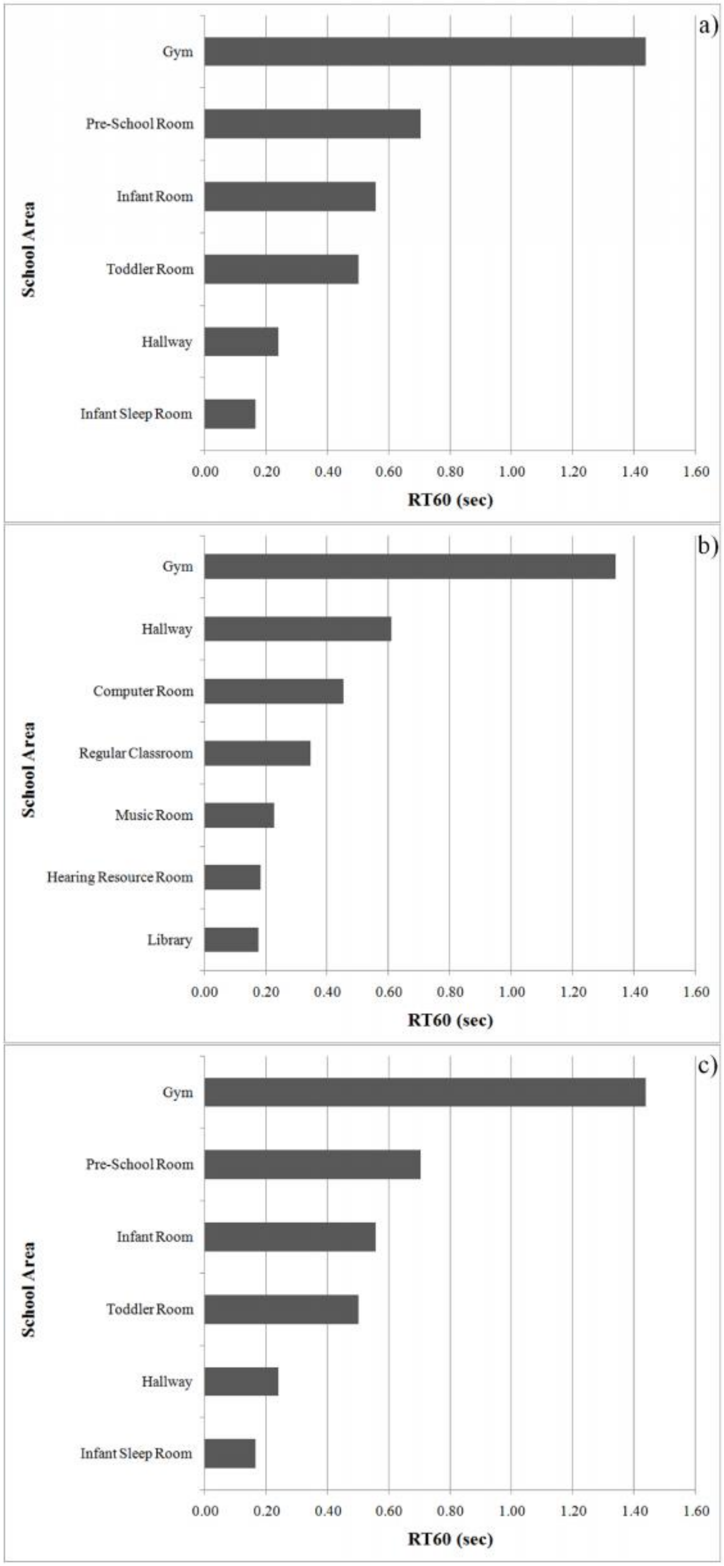

Figure 2-1: Bar graphs showing reverberation time (RT_{60}) for various rooms at the daycare (panel a), elementary (panel b), and high school (panel c) sites.

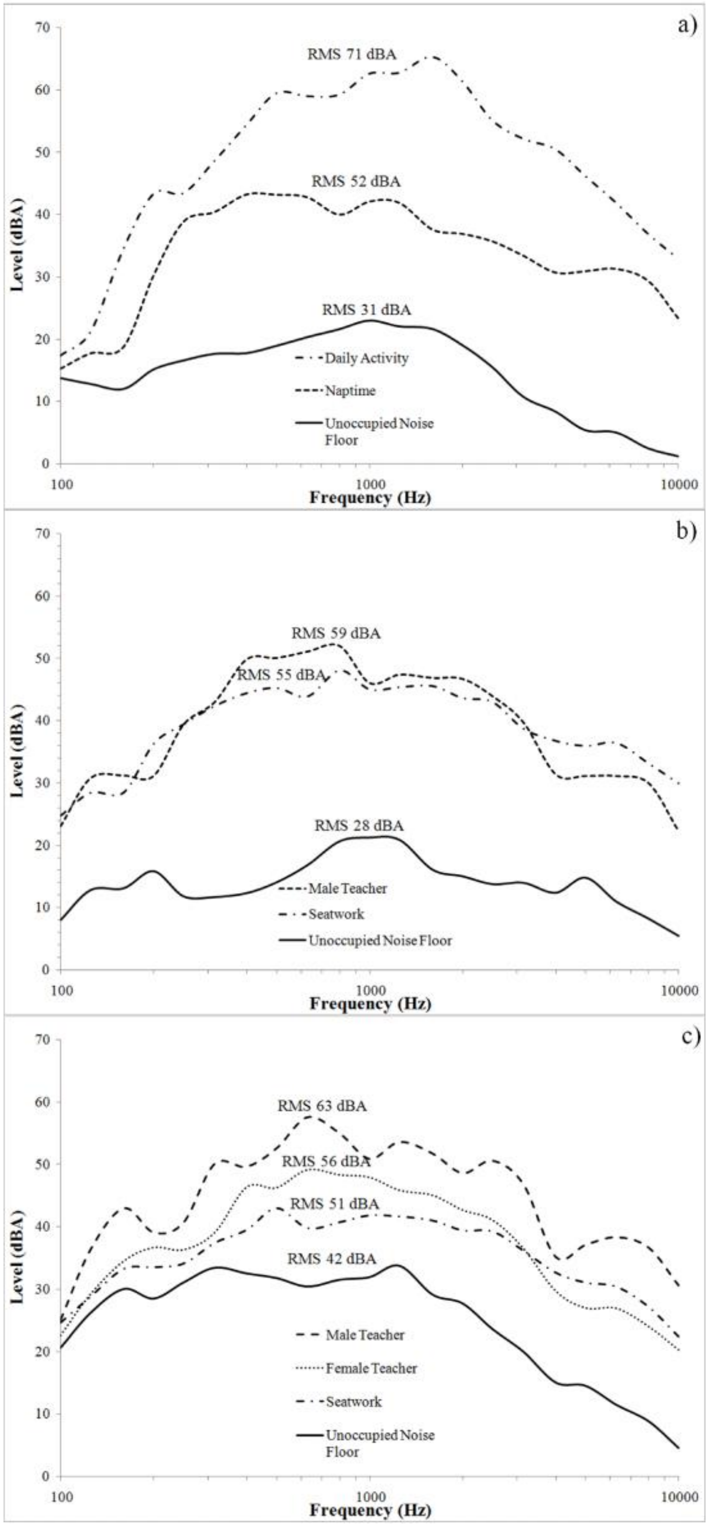

Figure 2-2: Amplitude spectra of sound recordings. Panels show: a) a pre-school daycare room, b) an elementary school classroom, and c) a high school classroom. Overall RMS level is shown above each curve.

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 2-2 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 room were likely the main factors contributing to the lower RT_{60}, and thus improved listening environment, of those rooms relative to the mainstream classrooms.

Table 2-2: Acoustic Characteristics of Classrooms across Sites

Room	RT_{60} (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	11b
Daycare			
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 Table 2-1 and Table 2-2. 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.

2.5.3 Sound Levels and Sources across the School Day

Dosimetry data show a large degree of variation in sound level over the course of a school day across all three sites (Figure 2-3). 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.

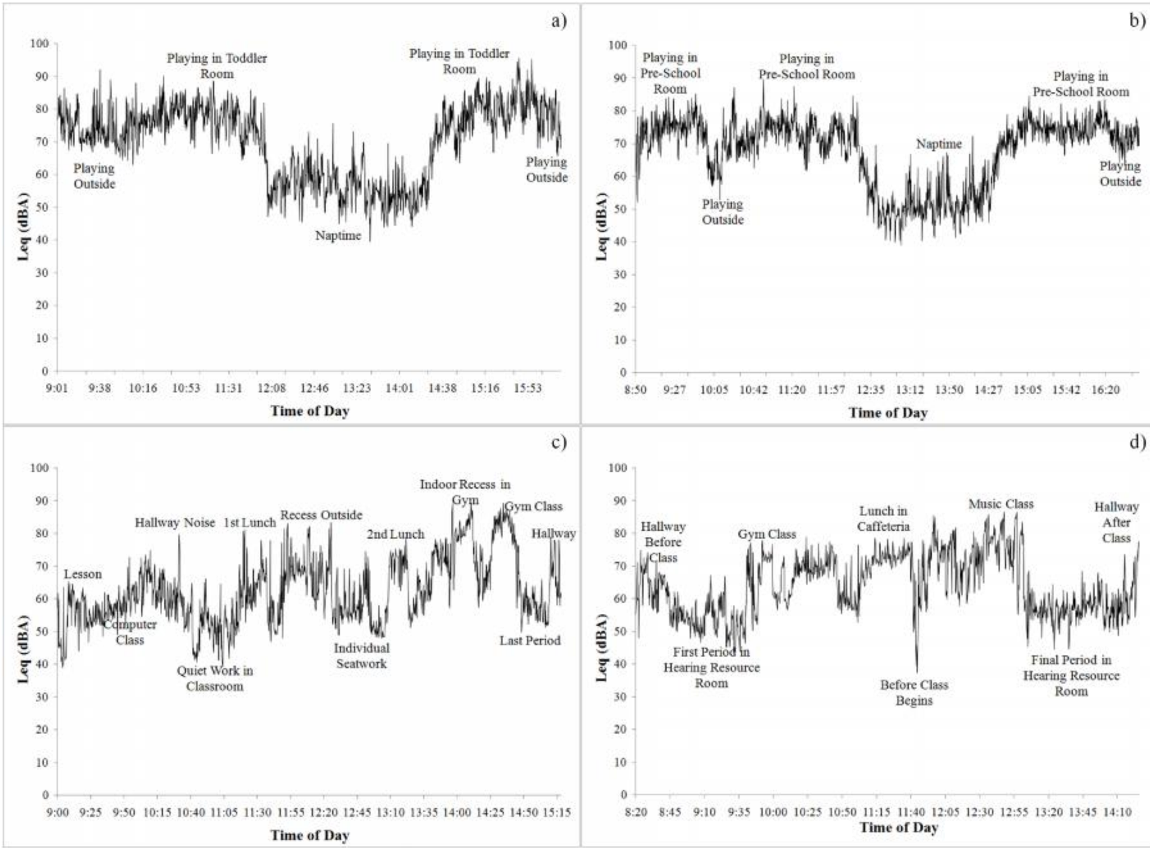

Figure 2-3: Dosimetry data shown as L_{eqA} by time at each observation site. Panels show: a) toddler room at daycare, b) pre-school room at daycare, c) elementary school, and d) high school. L_{eqA} curves are labeled with events and environments from observation records.

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 2-4. 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 (25^{th} percentile), with the upper edge of the box representing the upper quartile (75^{th} percentile). Whiskers 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 level 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.

Charted notes made during the observations were analyzed to yield the proportion of time the children spent in several environments (Figure 2-5). Children spent the majority of their time in a mixture of speech in noise across all three sites, and seldom were in situations classified as quiet, speech alone, or noise alone. In the daycare setting there was no time considered to be quiet 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 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.

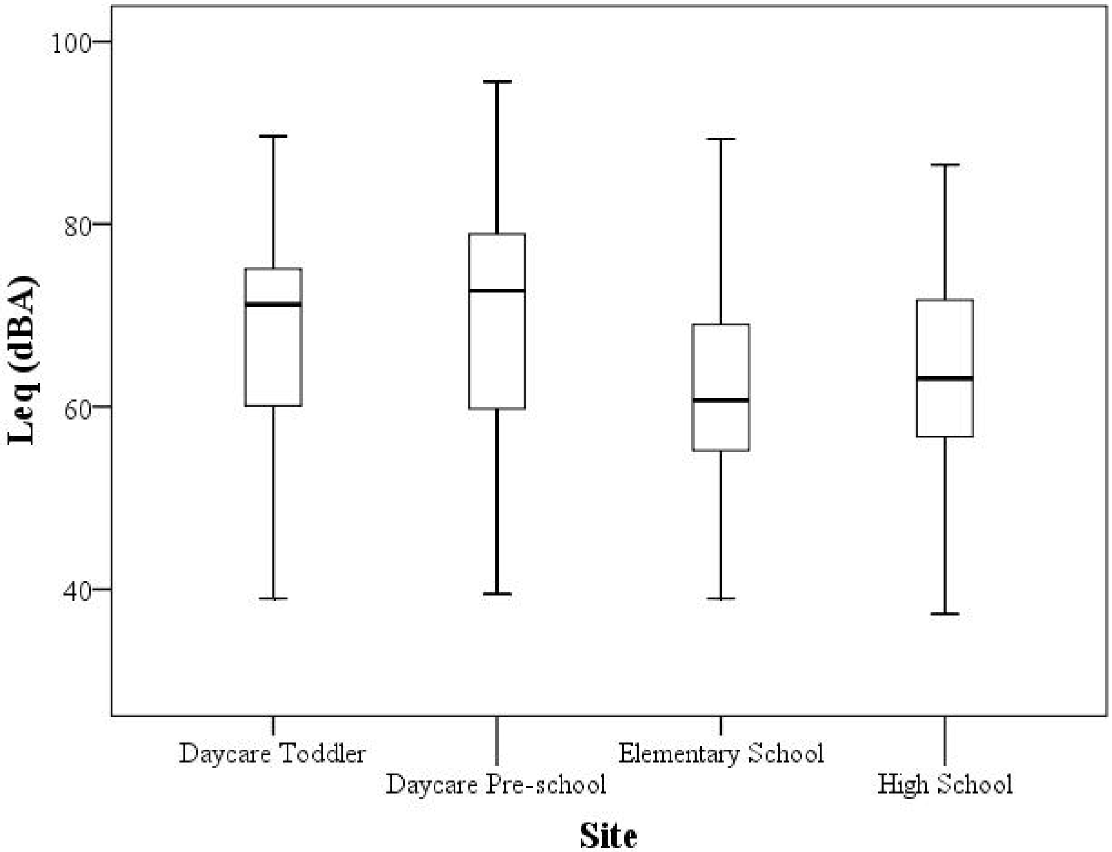

Figure 2-4: Boxplots depicting the L_{eqA} data for each observation site.

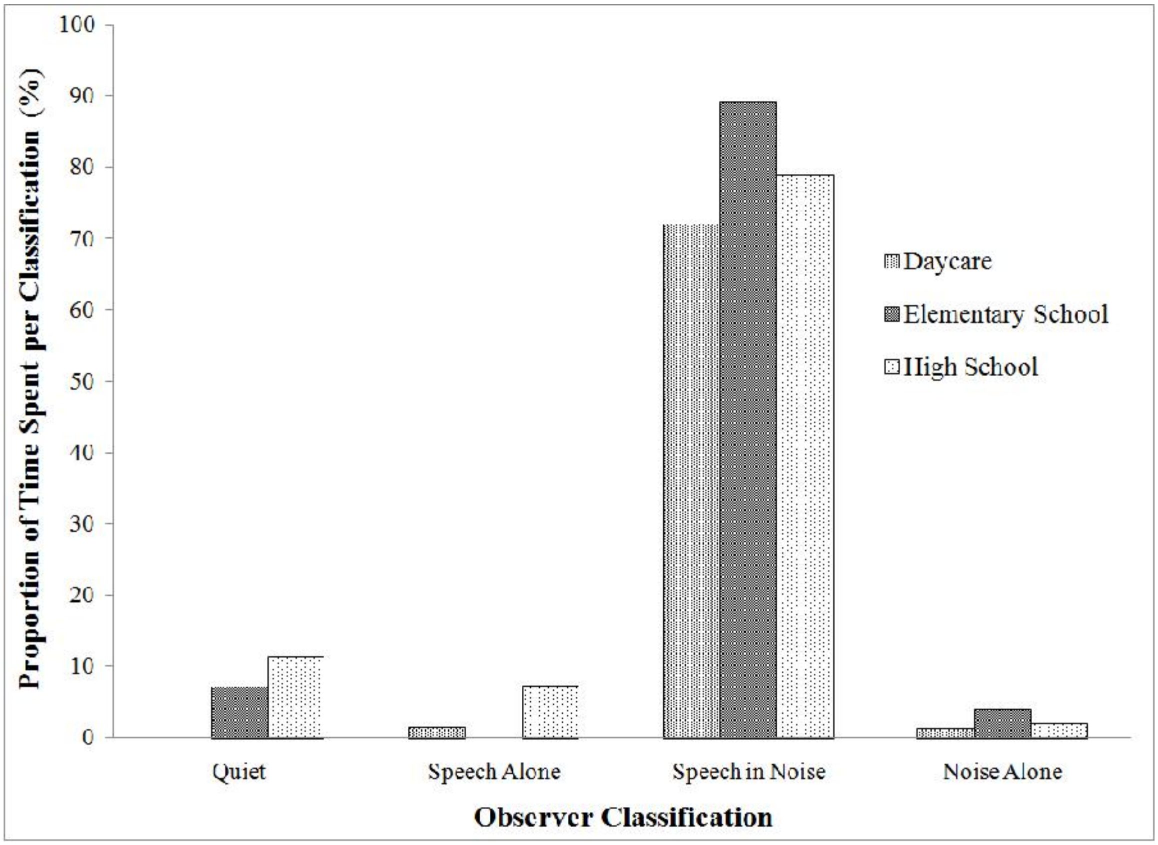

Figure 2-5: Proportion of time spent in each sound environment at each site as classified by the observer.

2.6 Discussion

2.6.1 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. Further, the types and levels of sound sources that children experience throughout their school days are also quite diverse. The details of these varied non-quiet listening environments and situations have been presented. Implications of these results will be discussed in the context of hearing instrument 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 at al. (2002) and Larsen and Blair (2008). The purpose of collecting RT_{60} and spectral data in the current study was to provide a framework 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, 2006b) 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, 2006b) 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. These data suggest that existing practice guidelines that recommend a single listening memory, which is optimized for communication-intensive environments (AAA, 2003; CASLPO, 2002), may not adequately serve children across the diverse range of their auditory ecology. Thus, children may need options for managing their diverse listening needs.

2.6.2 Implications for Hearing Instruments

Current practice guidelines are mixed with regard to using noise management strategies in pediatric hearing instrument fittings. Some state that there is insufficient evidence to warrant use of advanced processing (AAA, 2003; Foley et al., 2009), others consider these strategies as viable options (Bagatto et al., 2010; CASLPO, 2002), while others recommend features such as directional microphones ubiquitously (King, 2010) . Two such strategies commonly used for adults include directional microphones and 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 is from the back or sides of the listener (Amlani, 2001; Auriemmo 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, 2005). The listener is expected to point his or her head toward the talker and close range listening is also assumed. The classroom environment may not allow children to benefit from directional microphones, as talker distance and location may be other than close by and frontal. 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, 2005; Bentler & Chiou, 2006; Bentler, Wu, Kettel, & Hurtig, 2008; 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, in children 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 in 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), and loudness management strategies have been suggested (Scollie et al., 2005). 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 classify listening situations as either “speech,” “noise,” or other types of signals (wind, music). A notable result emerges from the combined data of Figure 2-4 and Figure 2-5. 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. Specifically, many non-quiet situations occur 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). These data 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 listening needs that extend beyond traditional classroom instruction. 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 situations such as hallway travel, playing team sports, and participating in group work, use of a personal FM system may not be optimal or practical. In these situations, other signal processing strategies may be effective for improving loudness comfort and/or speech understanding. Thus, these data may inform future work on hearing instrument signal processing for children across multiple environments.

2.6.3 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. Further, 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 generalizability. Future research could pursue a large-scale investigation of the acoustics, dosimetry characteristics, or classification of non-classroom environments.

2.6.4 Next Steps

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 6 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 generalizability. 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.

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. Further, 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 instrument technology offers a variety of options for management of either loud sounds or sounds with low SNR. In chapters 3 and 4, experimental studies of hearing aid signal processing strategies will specifically evaluate technologies intended for either loudness management of high-level signals, or management of signals embedded in a background of noise.

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Chapter 3

3 Children's Speech Recognition and Loudness Perception with the Desired Sensation Level v5 Quiet and Noise Prescriptions

3.1 Introduction

The purpose of the current study was to compare children's performance on tasks of consonant recognition, sentence recognition in noise, and loudness perception while wearing hearing instruments fitted with two prescriptions from the Desired Sensation Level (DSL) hearing instrument prescription algorithm, specifically the DSL v5 Quiet and DSL v5 Noise prescriptions were evaluated.

3.2 Hearing Instrument Prescription

Since its inception, the DSL method has had a specific focus on pediatric hearing instrument use. Since the development of DSL v3, the algorithm has sought to maximize audibility across frequencies while remaining within the auditory range (above threshold and below level of discomfort) across the amplified frequency range (Dillon, 2001; Gagné, Seewald, Zelisko, & Hudson, 1991a; Gagné, Seewald, Zelisko, & Hudson, 1991b; Seewald, Ross, & Spiro, 1985). The advent of non-linear amplification in hearing instruments led to expanded goals for prescriptive formulae. Algorithms intended for use with non-linear hearing instruments aimed to provide frequency-gain responses for speech at levels both above and below the average level of conversational speech (e.g., prescriptive targets for speech at a low level such as 50 dB SPL, and a high level of 75 dB SPL) (Byrne, Dillon, Ching, Katsch, & Keidser, 2001; Cornelisse, Seewald, & Jamieson, 1995). DSL v4.1 was developed to incorporate the application of non-linear circuitry, which allowed for normalization of loudness across a broad range of input levels (Jenstad, Pumford, Seewald, & Cornelisse, 2000; Jenstad, Seewald, Cornelisse, & Shantz, 1999; Scollie et al., 2005). Maximizing the audibility of speech sounds across input levels is especially important in the prescription of hearing instruments for children (AAA, 2003; CASLPO, 2002; The Pediatric Working Group, 1996); research has shown that children with hearing loss require more audibility and a larger bandwidth in order to perceive and thus develop language (Pittman & Stelmachowicz, 2000; Stelmachowicz, Hoover, Lewis, Kortekaas, & Pittman, 2000; Stelmachowicz et al., 2007; Stelmachowicz, Pittman, Hoover, & Lewis, 2001; Stelmachowicz et al., 2004a). The literature regarding speech recognition abilities of children who wear hearing instruments fitted with a DSL prescription shows that these children generally achieve consonant recognition scores in the 80 to 95% correct range on average (Jenstad et al., 1999; Scollie, 2008; Scollie et al., 2010b; Sininger, Grimes, & Christensen, 2010). Also, lower gain prescriptions can lead to decrements in speech recognition performance at lower input levels for some children (Scollie et al., 2010b).

Studies of speech-in-noise recognition with children who wear hearing instruments have shown a range of signal-to-noise ratios (SNR) required for 50% correct performance of approximately ±5 dB (Ng, Meston, Scollie, & Seewald, 2011). Although audibility is a likely factor in performance, previous research has indicated no difference in speech-in-noise recognition between hearing instrument prescriptions, specifically when used to compare the DSL v4.1 and National Acoustics Laboratories Non-Linear (NAL-NL1) frequency responses in combination with non-linear amplification (Scollie et al., 2010b).

Studies of aided loudness perception have shown differences in loudness ratings between hearing instruments fitted with linear and wide dynamic range compression (WDRC), with WDRC instruments resulting in lower reported loudness for loud sounds than linear instruments (Jenstad et al., 2000; Jenstad et al., 1999). Loudness differences have also been reported between hearing instruments fitted with prescriptions with different levels of prescribed gain, with lower gain prescriptions resulting in lower reported loudness ratings (Scollie et al., 2010b).

The most recent version of DSL (version 5), introduced separate sets of prescriptive targets for individuals with congenital and acquired hearing loss as well as separate prescriptions for use in quiet and noisy situations (Scollie et al., 2005). The noise program prescription within the DSL v5 fitting method is designed for use as an additional hearing instrument memory with an alternate frequency response and reduced gain (Scollie et al., 2005). The prescribed frequency response is designed to maintain audibility of the frequency regions of speech believed to contain acoustic cues most important for speech intelligibility based on the Speech Intelligibility Index (SII, ANSI S3.5, 1997). Additionally, the prescribed compression threshold is elevated by 10 dB in order to reduce the gain applied to lower-level background noise. Relative to the prescription for quiet environments, the noise program prescription places speech at a lower sensation level at low and high frequencies and provides less gain for low-level sounds. According to Scollie et al. (2005), this prescription is designed to manage comfort in noisy environments and is not expected to improve speech recognition in the presence of background noise.

3.3 Limitations of Current Hearing Instrument Prescriptions

Although the DSL prescriptive method has evolved in a way that allows for somewhat different listening situations (i.e. a single speech-source at varied levels), the scope of hearing instrument prescription may still be considered narrow when compared to the number of listening environments and situations experienced by listeners on a day-to-day basis, many of which include multiple talkers. Multi-talker environments often include background noise, competing speech, and reverberation (Brungart & Simpson, 2007; Cherry, 1953; Scollie et al., 2010a), and may be broadly characterized as “noisy” listening situations. Difficulty understanding speech-in-noise is a leading cause of listeners’ dissatisfaction with hearing instruments (Kochkin, 2007). Real-world, non-quiet listening environments can be divided into two general categories, i) speech amidst moderate background noise, a situation in which speech clarity is a primary goal, and ii) loud environments, a situation in which comfort is a primary goal.

Research has indicated that children experience background noise levels ranging from approximately 40 to 80 dBA across the variety of environments they typically encounter on a daily basis (Crandell & Smaldino, 2000; Olsen, 1998; Pearsons, Bennett, & Fidell, 1977). Recall from the observations in Chapter 2 that the children in the study experienced noise levels ranging from 40 to greater than 90 dBA over the course of a school day. These reported broad ranges of noise levels result in an equally broad range of signal-to-noise ratios (SNR) across the environments children experience in a given day. Listening across these environments ranges from very difficult to relatively easy when SNR is low or high, respectively. As discussed in Chapter 1, children with hearing loss experience greater listening difficulty when background noise is present and require higher SNRs than children with normal hearing in order to understand speech (Elliott, 1979; Fallon, Trehub, & Schneider, 2002; Kortekaas & Stelmachowicz, 2000; Pittman & Stelmachowicz, 2000; Scollie, 2008; Stelmachowicz et al., 2000; Stelmachowicz et al., 2001; Stelmachowicz et al., 2004b). Although the challenges presented by the range of noise levels and SNRs in a child's daily life exists for all children, the needs of children with hearing loss, who use hearing instruments, are unique.

In a series of studies that compared NAL-NL1 and DSL v.4.1 non-linear prescriptive algorithms in children, unique listening needs and preferences of children with hearing loss were identified (Ching, Scollie, Dillon, & Seewald, 2010a; Ching et al., 2010b; Ching et al., 2010c; Scollie et al., 2010a; Scollie et al., 2010b). The authors reported two principal listening components in their analysis of listening preference: 1) loud, noisy, and reverberant situations (shopping mall, restaurant, car/bus/train, playground), 2) quiet or low-level listening situations; specifically: friends in class, soft speech, sounds from behind, teacher in class, and sounds in the environment (Scollie et al., 2010a).

Ching et al. (2010b) described the electroacoustic properties and differences between fittings for the children. In general, the DSL fittings provided more gain across frequencies than NAL fittings and the NAL fittings had steeper response slopes than DSL fittings. DSL v4.1 prescribed approximately 10 dB more low-frequency gain than NAL-NL1 across input levels. DSL v4.1 prescribed approximately 5 dB more high-frequency gain for low- and high-level inputs (55 and 80 dB SPL, respectively) and approximately 10 dB more high-frequency gain for moderate input levels (70 dB SPL).

Children expressed mixed preferences for the two fitting rationales. Children demonstrated a preference for the DSL fitting when listening to lower-level sounds or when they desired louder and clearer output. Some children demonstrated a preference for the NAL fitting when listening to louder signals or when listening in the presence of background noise. However, children also indicated a preference for having access to both fitting rationales as separate programs to be selected depending on a given listening situation. The authors concluded that level, location, and SNR of target sounds were important factors that contributed significantly to children's listening preferences, and that children required different amplification characteristics for the varied listening environments they encountered during daily living. One clinically achievable suggestion for fitting to meet these needs was application of a noise program that can be manually selected as needed (Scollie et al., 2010a).

3.4 Rationale for Current Study

Current hearing instrument prescription guidelines do not offer recommendations for non-quiet situations (AAA, 2003; CASLPO, 2002; Foley, Cameron, & Hostler, 2009). Although there are no current recommendations for noise management in pediatric hearing instrument fittings, children have demonstrated a desire for non-quiet amplification options (Scollie et al., 2010a).

Modern hearing instruments currently offer three main options for managing listening in noise. Frequency-gain shaping is the adjustment of the amount of amplification provided across the frequency range. Directional microphone systems use more than one microphone to reduce the amplification of sounds coming from locations other than that of the desired sound source. Digital noise reduction (DNR) involves digital signal processing to identify and minimize unwanted noise in the hearing instrument's output. The DSL v5 Noise prescription is an example of a frequency-gain shaping approach.

In summary, modern hearing instruments offer a number of options to manage non-quiet listening. These technologies may be used together or in isolation, yet few data exist regarding their performance in children who have hearing loss. An evaluation of children's performance with these available non-quiet management options is therefore warranted. In clinical practice, signal processing options (directional microphones, DNR) are typically used in combination with a specific frequency-gain response. Because the frequency-gain response itself is expected to directly influence the speech recognition and loudness outcomes of a hearing instrument fitting, understanding the outcomes associated with specific shaping strategies may enable an evidence-based approach to a frequency-gain response for use in non-quiet situations. This prescription could then serve as a base for the evaluation of additional signal processing. For the purposes of the present study, outcomes associated with speech in quiet, speech in noise, and loudness perception were evaluated for the DSL v5 prescriptions for quiet and noisy listening.

3.5 Research Questions

The current study addresses three research questions regarding the DSL v5 Quiet and Noise prescriptions. First, does use of the two prescriptions result in differences in consonant recognition? Second, does use of the two prescriptions result in a difference in sentence recognition in noise performance? Third, does use of the two prescriptions result in different comfort ratings for loud sounds? The experimental design used to address these questions is summarized in Appendix A.

3.6 Methods

3.6.1 Participants

Eleven children were recruited to participate in the study. Participants included five children from an elementary school self-contained class for the deaf and hard of hearing and six children from a high school hearing resource class. The average age of the elementary school children was 8.85 years (range: 8.0 to 9.75 years); the average age of the high school children was 15.18 (range: 13.83 to 17.58 years). Both schools were located in London, Ontario and are a part of the Thames Valley District School Board's Deaf and Hard of Hearing Program. All participants were full-time hearing instrument users with stable, congenital sensory-neural hearing losses.

Data from previous research evaluating children's performance on the UWO-DFD with two different prescriptions (Scollie et al., 2010b) was used for sample size estimation. Results indicated a total sample size of 12 individuals would be sufficient to detect the hypothesized effect of a two-level within-subject independent variable 71.3% of the time at a 0.05 alpha level (Lee, 2004).

3.6.2 Hearing Threshold Levels

Hearing threshold levels were measured by the participants' clinical audiologists within six months prior to study enrollment. Hearing losses ranged from moderate to profound (Figure 3-1). Most of the participants (8 out of 11) had symmetrical hearing losses, with symmetrical hearing loss defined as less than a 15 dB difference in four-frequency pure-tone average between ears.

3.6.3 Hearing Instrument Fitting Procedure

Hearing instruments were fitted using individual ear canal acoustic measurements in the form of Real-Ear to Coupler Difference (RECD) measurements performed with the Audioscan RM500SL Hearing Instrument Fitting System according to recommended procedures (Bagatto et al., 2005). All participants were fitted with behind-the-ear hearing instruments with instrument performance verified using the simulated real-ear measurement (sREM) feature of the Audioscan RM500SL to measure hearing instrument output relative to prescriptive targets.

3.6.3.1 Target Derivation

DSL v5 Quiet prescription targets were generated by the RM500SL and custom software was used to generate targets for the DSL v5 Noise prescriptions using the participants' audiometric thresholds and RECDs. DSL v5 Quiet prescriptive targets were calculated for input levels of 55, 65, and 70 dB SPL. DSL v5 Noise prescriptive targets were calculated for input levels of 55, 65, and 75 dB SPL.

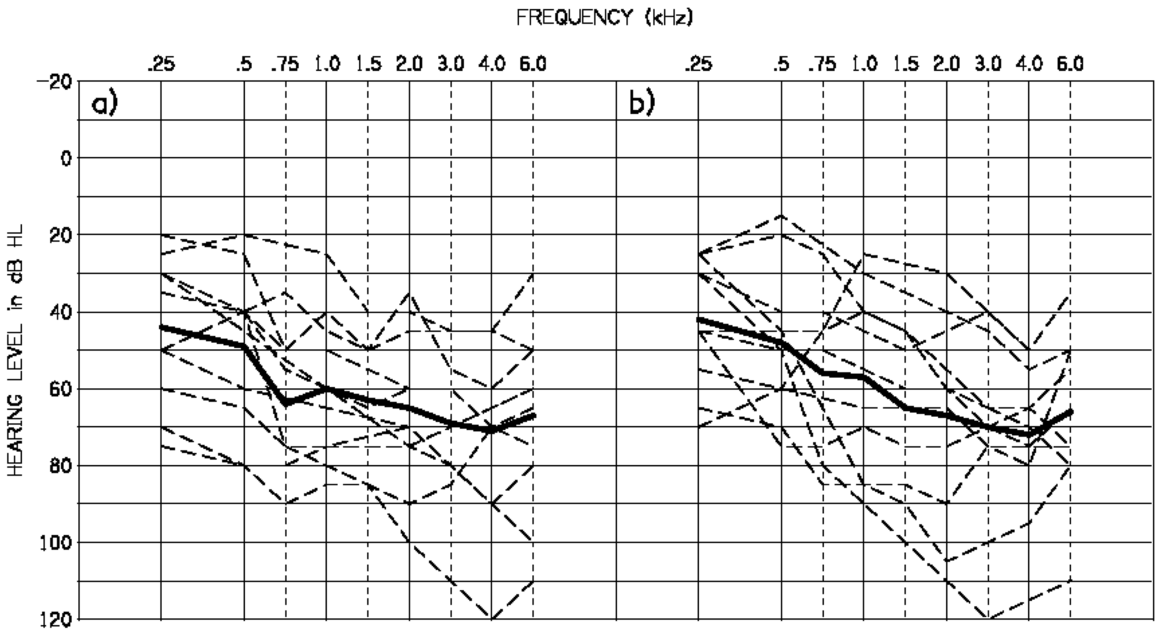

Figure 3-1: Audiometric thresholds for all subjects. Panel a shows left ear thresholds, panel b shows right ear thresholds; bold lines are average audiograms.

3.6.3.2 Hearing Instrument Adjustment and Verification

All participants were fitted with Phonak Versata SP behind-the-ear hearing instruments. Hearing instruments were adjusted in an HA2-2cc coupler to match the real-ear aided response (REAR) targets for both prescriptions using the speech signal generated by the Audioscan RM500SL across input levels. The hearing instruments were manually adjusted to match targets from 250 to 6000 Hz. For 9 of the 11 participants, targets could be met to 6000 Hz using the multichannel amplitude compression processing. Two remaining participants had steeply sloping hearing losses and could not be provided with a broad audible band of speech. For these two participants, Phonak SoundRecover was enabled in their fittings with cut-off frequencies of approximately 2000 Hz. SoundRecover is a proprietary form of non-linear frequency compression, which compresses the high-frequency output of the hearing instrument into a lower frequency-range in which the listener has better hearing sensitivity (Simpson, Hersbach, & McDermott, 2005). The specific settings were verified and fine tuned following previously suggested procedures (Bagatto, Scollie, Glista, Parsa, & Seewald, 2008; Glista & Scollie, 2009; Glista et al., 2009).

Hearing instruments were fitted to match targets within 0.97 dB (± 1.12 dB) for the DSL v5 Quiet prescription and within 1.54 dB (± 1.37 dB) for the DSL v5 Noise prescription, averaged across ears, frequencies, and input levels. This target matching evaluation excluded frequencies above 2000 Hz for the two subjects with Sound Recover enabled. The fittings to the DSL v5 Quiet and Noise prescriptions were stored to hearing instrument fitting software for later use as experimental listening conditions.

The difference between fittings using the DSL v5 Noise prescription relative to the DSL v5 Quiet prescription is shown in Figure 3-2, which illustrates the difference between DSL v5 Quiet and Noise targets for the better hearing ear of each participant. The figure demonstrates the lower gain and speech-importance weighting of DSL v5 Noise relative to Quiet targets. On average, DSL v5 Noise targets are approximately 10 dB lower for low frequencies and approximately 5 dB lower for high frequencies when compared to DSL v5 Quiet targets.

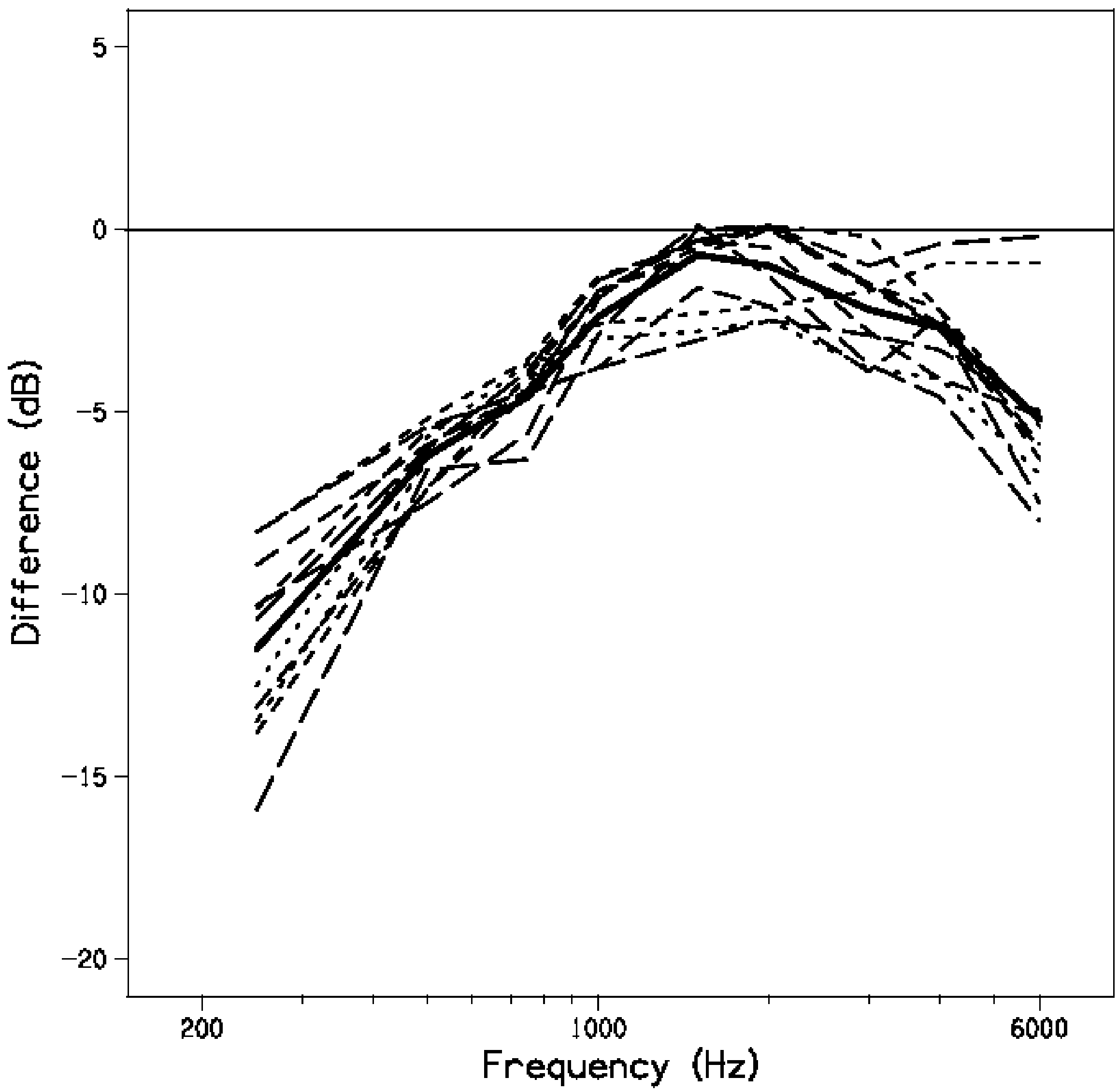

Figure 3-2: Difference between DSL v5 Noise and Quiet prescriptive targets for 65 dB SPL speech input. Negative numbers indicate less output with the DSL v5 Noise prescription. The solid bold line represents the overall average difference between targets.

Participants wore the hearing instruments for a period of two weeks prior to data collection in order to acclimate to their new devices. During the second week of acclimatization, each participant had two practice sessions to familiarize them with the tasks in the study. Middle ear status was monitored by immittance testing with a Maico MI26 portable tympanometer at the beginning of each data collection session. If the tympanometry results differed from previous measurements, testing was delayed until tympanometry results agreed with previous results.

3.6.4 Equipment

A test system comprised of a laptop running custom software and a custom-built external hardware interface was used to control the presentation of test stimuli and record subject responses for the outcome measures. Target stimuli were presented from 0° azimuth through a tripod-mounted Simeon 500WU powered speaker at a height of 1.4 m to the center of the speaker. Competing stimuli were presented from 180° through a Simeon 900AU Omnipanel speaker system at a height of 1.5 m to the center of the speaker. The Simeon Omnipanel speaker was chosen because it is a distributed mode loudspeaker (DML), which uses multiple piezoelectric elements in place of conventional electromagnetic coils. DMLs disperse sound in a spherical pattern, which is essentially random and therefore less phase-related than conventional speakers (Bai & Huang, 2001). The speakers were positioned approximately 6 m apart with the participant seated between them (approximately 3 m from each speaker).

The test system was set up within a classroom at both the elementary and high school. The room at the elementary school measured 9.5 m long by 7.0 m wide by 2.4 m high; the room at the high school measured 10.4 m long by 5.1 m wide by 7.7 m high. Prior to data collection the reverberation time and noise floor of the two rooms were estimated using a computerized system equipped with SpectraPlus software (Pioneer Hill Software LLC, 2008). The RT_{60} estimates were 200 ms and 550 ms for the elementary and high school rooms respectively; noise floor estimates were 21.7 dBA and 31.0 dBA for the elementary and high school rooms respectively.

3.6.5 Outcome Measures

3.6.5.1 Consonant Recognition

The consonant recognition task was a modified version of The University of Western Ontario Distinctive Features Differences test (UWO-DFD; Cheesman & Jamieson, 1996). The computer-controlled system was used to present the test stimuli, which consisted of 21 consonants (C = **b, ch, d, f, g, h, j, k, l, m, n, o, p, r, s, sh, t, th, v, w, y,** and **z)** presented in a nonsense disyllable format (/λ**C**IL/). The test was originally developed with two male and two female talkers. For this study, one male and one female talker were used with each talker presenting the 21 disyllables twice each for a total of 84 nonsense disyllable presentations at both presentation levels. This modification was made to divide the task into two blocks of 42 presentations by the same two talkers at each presentation level in order to assess test-retest reliability of the participants. A visual list of the 21 consonant sounds were displayed on a computer monitor and participants were asked to select the sound they heard by clicking the respective sound on the screen with a computer mouse. The test stimuli were presented from the front speaker at 50 and 70 dB SPL in the test position, which was calibrated at the start of each day. The order of prescription condition was counter-balanced across subjects.

3.6.5.2 Sentence Recognition in Noise

The Bamford-Kowal-Bench Speech in Noise test (BKB-SIN; Niquette, 2003) was administered through the computer controlled system according to the test manual's instructions (Etymotic Research, 2005). The test system was calibrated daily using the speech-shaped noise provided on the test CD. The target level from both the target signal speaker and competing noise speaker was 70 dB SPL at the test position, and tolerance for daily checks was ±0.5 dB.

The split tracks from the CD at fixed SNR values were used to present target sentences from the front speaker and competing four-talker babble from the rear speaker. Three list pairs were administered in each prescription condition. A difference of more than 2 dB between conditions is considered significant given the administration of three list pairs with the age range of this study's participants. The order of prescription was counter-balanced across subjects (Etymotic Research, 2005).

3.6.5.3 Loudness Perception

The Contour Test of Loudness Perception (Cox, Alexander, Taylor, & Gray, 1997; Cox & Gray, 2001) was administered in the sound field according to the methods of Cox and Gray (2001) with the following modifications. Two conditions were tested i) sentences in quiet and ii) sentences in noise. Materials from the BKB-SIN were used for both conditions. In the sentences in quiet condition, groups of four BKB sentences were presented first in ascending 4 dB steps from 52 to 80 dB SPL and then in descending 4 dB steps back down to 52 dB SPL from the speaker in front of the subjects. For the sentences in noise condition, groups of 4 BKB sentences were presented from in front of the listener while the four-talker babble was presented from behind the listener. The SNR of the sentences relative to the babble was fixed at +10 dB. This SNR was chosen to allow the sentences to be distinguished from the babble. The overall presentation level began at 52 dB SPL and ascended in 4 dB steps to 80 dB SPL and then descended in 4 dB steps back down to 52 dB SPL. Loudness perception categories spanned 8 levels (0 = did not hear, 1 = very soft, 2 = soft, 3 = comfortable but slightly soft, 4 = comfortable, 5 = comfortable but slightly loud, 6 = loud but okay, 7 = uncomfortably loud). For both conditions, the task would automatically reverse direction after the presentation level reached 80 dB SPL or as soon as 'uncomfortably loud' was selected, whichever happened first.

The categorical ratings were shown as text on a computer monitor in front of the participant and they were asked to click their elected rating with a computer mouse after presentation of each group of four sentences at each level. To assist the younger participants with the task, the categories were combined with pictures on a sheet of paper; the participant would point to their elected rating on the paper (Figure 3-3) and the researcher would select the corresponding category on the computer monitor. The order of prescription and loudness perception conditions were counter-balanced across participants.

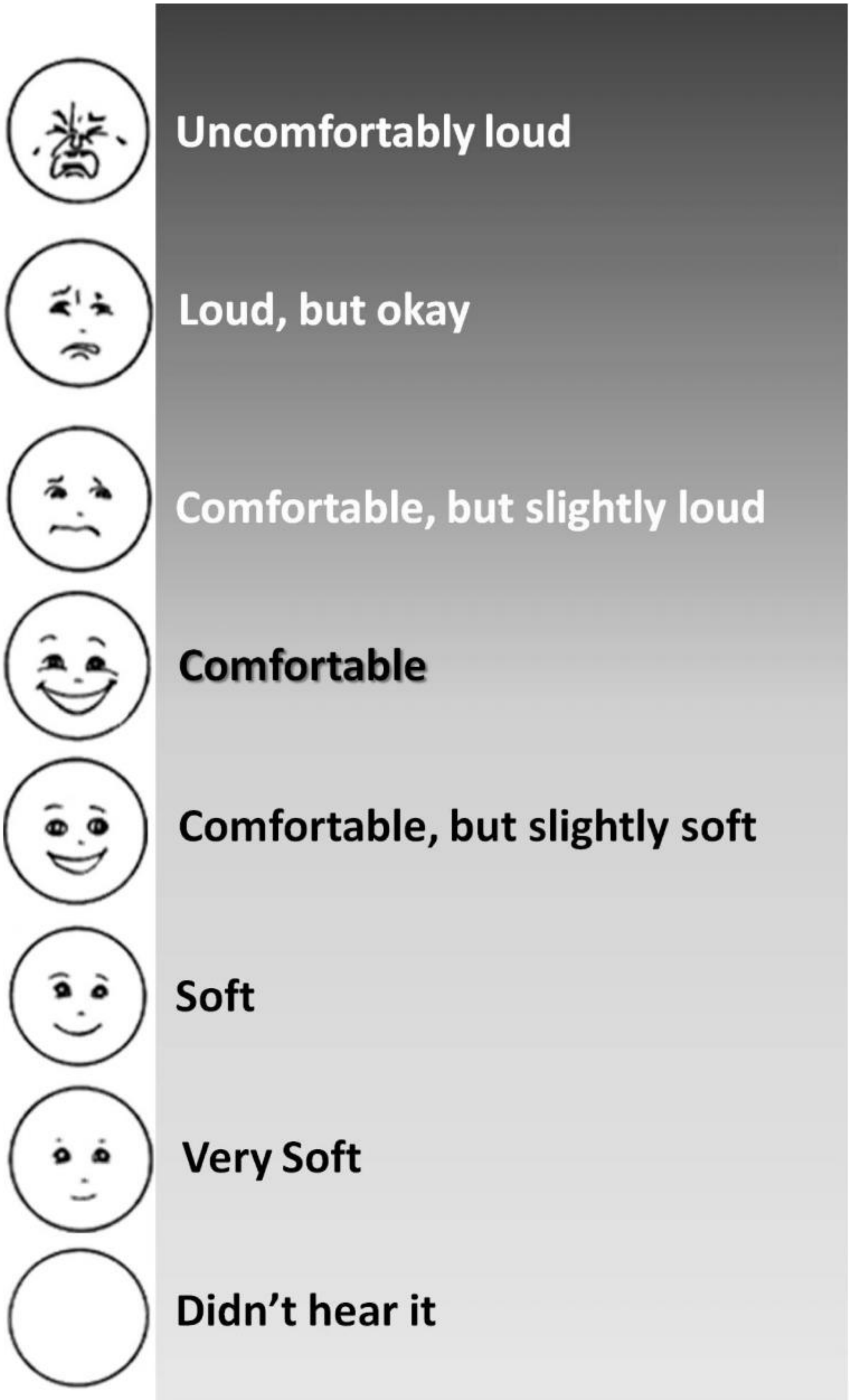

Figure 3-3: Response categories for loudness perception task.

Based on the data reported by Jenstad et al. (1997), loudness ratings from the ascending and descending runs were averaged together to create a single loudness rating for each input level for analysis. In instances where the participant selected ‘uncomfortably loud’ before presentation at 80 dB SPL, thus reversing the direction of the task, missing data were replaced with ‘uncomfortably loud’ ratings. For example, if a participant rated 72 dB SPL as ‘uncomfortably loud’, ‘uncomfortably loud’ was then also inserted as the rating for 76 and 80 dB SPL.

3.6.6 Test Administration Details

Children were blinded to conditions. The researcher was not blind to conditions; however, for the computer-administered tasks (consonant recognition and loudness perception), the researcher was not involved in the scoring of the data and thus the effect of blinding was achieved. For the BKB-SIN, the researcher scored the task and thus blinding was not achieved. Test order was kept constant, with test order effects addressed by counter-balancing the sequence of hearing instrument conditions across participants.

3.7 Results

Following the recommendation of Max and Onghena (1999), the Greenhouse-Geisser correction was used to adjust degrees of freedom universally in all repeated measures analyses of variance reported below in order to control for any potential violations of the sphericity assumption.

3.7.1 Consonant Recognition in Quiet

Raw scores for the consonant recognition in quiet task ranged from 45 to 98% correct across participants, levels, and prescriptions. The test-retest difference between blocks of 42 presentations averaged 3.5% (range 0 to 16.7%) across participants, levels, and prescriptions. Raw percent correct scores for all participants across levels are shown in Figure 3-4 by prescription, along with the 95% confidence interval for significant difference between scores for the task. Only one score was significantly higher with DSL v5 Quiet than with DSL v5 Noise.

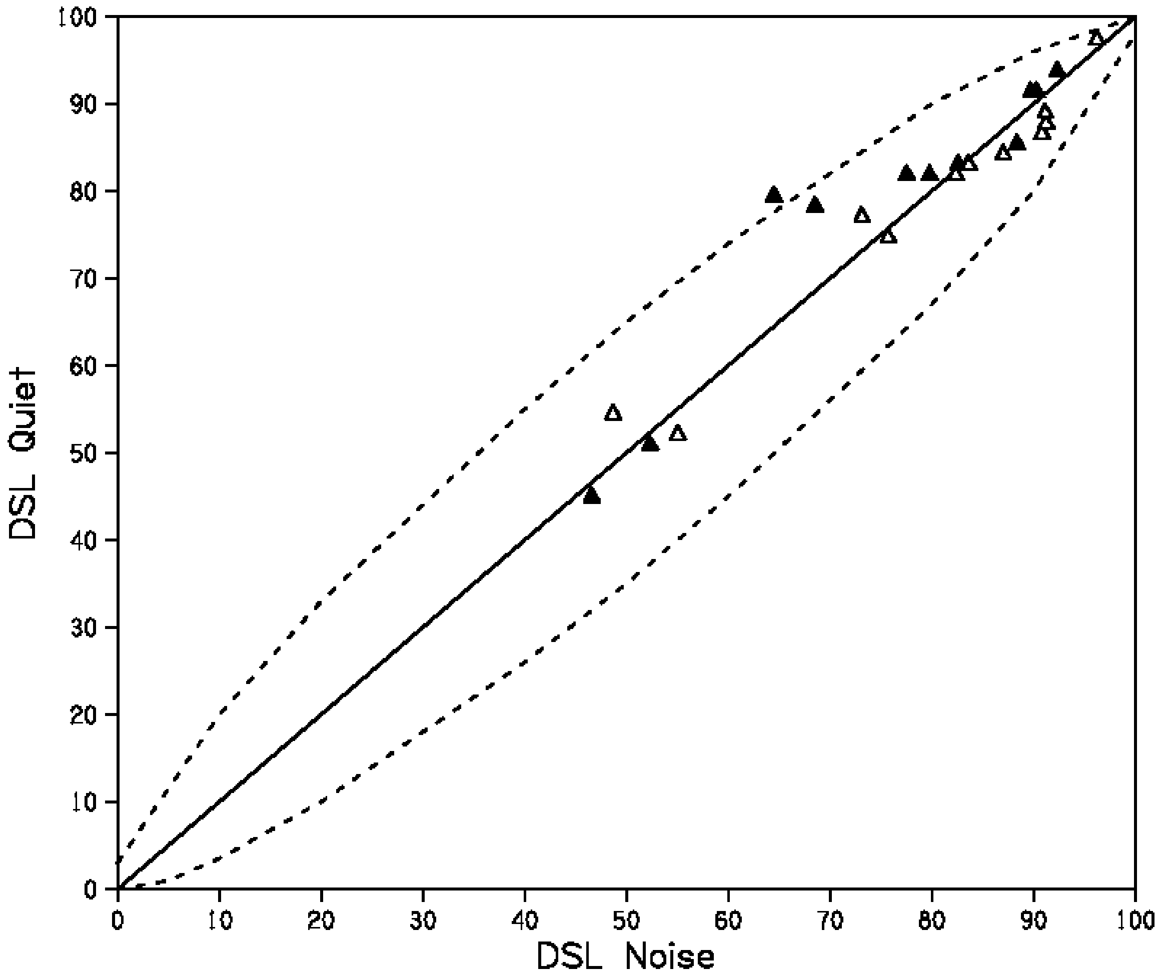

Figure 3-4: Individual scores on the consonant recognition task (in percent correct) across level and prescriptions. Filled symbols represent scores at an input level of 50 dB SPL and open symbols represent scores at an input level of 70 dB SPL. Dashed lines indicate the 95% confidence interval for significant change in individual score.

Raw scores were converted to rationalized arcsine units (RAU: Studebaker, 1985) for analysis. RAU scores were analyzed using the General Linear Model repeated measures analysis of variance (SPSS v16.0) with level (two levels) and prescription (two levels) as repeated measures within-subjects factors. Results indicated that there was a significant main effect of level ($F(1,10) = 7.86$, $p = 0.02$, $\eta^2 = 0.44$). The main effect of prescription was not significant ($F(1,10) = 4.85$, $p = 0.052$, $\eta^2 = 0.33$). There was a significant interaction between prescription and level ($F(1,10) = 5.270$, $p = 0.04$, $\eta^2 = 0.34$). Post-hoc testing of performance across level indicated that performance varied with level for the DSL v5 Noise prescription ($t(10) = 4.03$, $p = 0.002$, $d = 8.59$) but not for the DSL v5 Quiet prescription ($t(10) = 0.47$, $p = 0.65$, $d = 0.83$). These results demonstrated a decrease in speech recognition scores for low-level speech for the DSL v5 Noise prescription. This change was 4.2% on average, and individual changes ranged from -2.4% (higher performance with DSL v5 Noise) to 10.7% (higher performance with DSL v5 Quiet). Mean percent correct scores are shown in Figure 3-5 for both test levels and prescriptions.

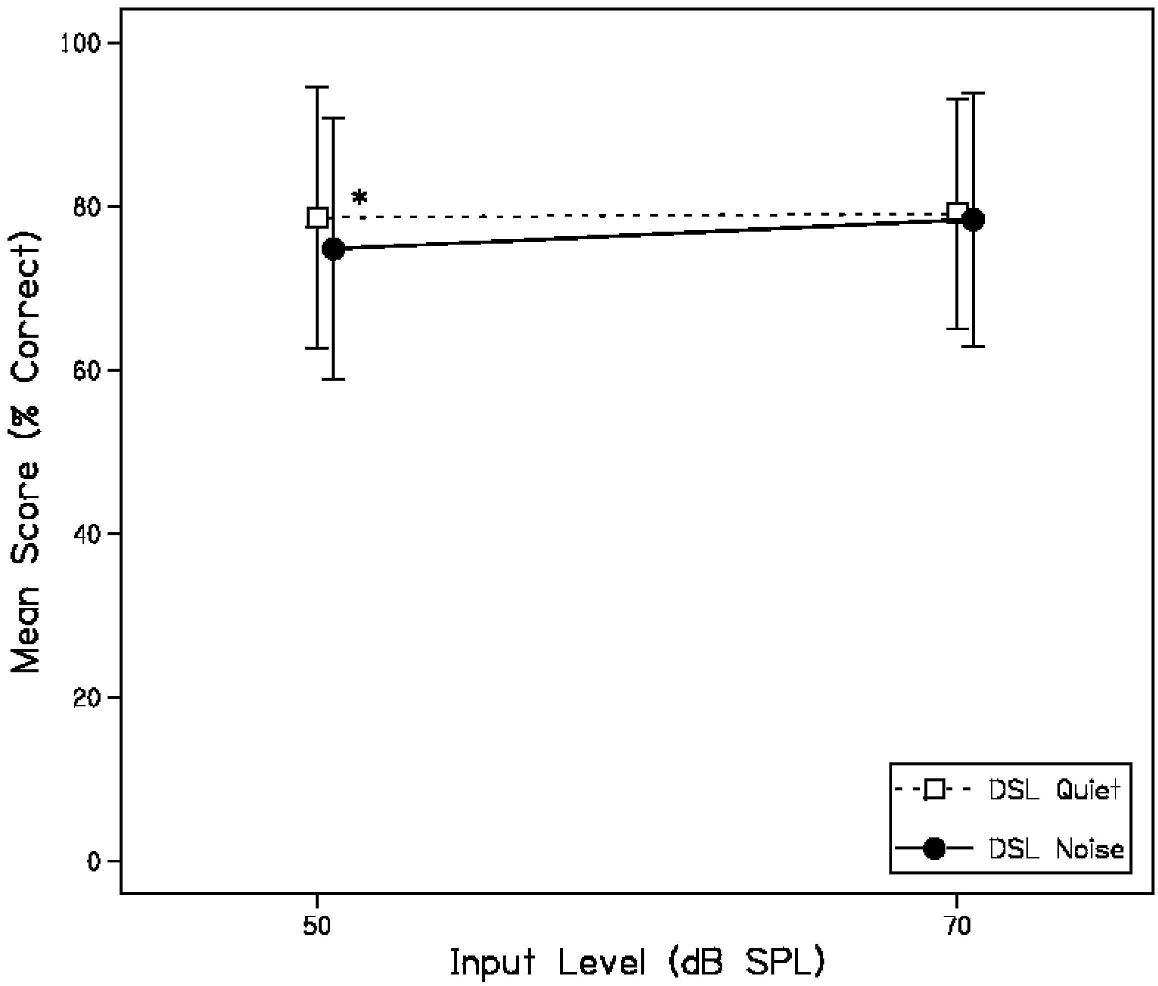

Figure 3-5: Mean consonant scores for 50 and 70 dB SPL by prescription. Vertical bars denote one standard deviation about the mean. Asterisk marks significant difference between scores.

3.7.2 Sentence Recognition in Noise

SNR-50 scores were averaged across three list pairs in each prescription. Average scores across participants ranged from -0.8 to 16.0 dB SNR. Individual SNR-50 scores are shown in Figure 3-6, for both prescriptions, along with the 95% confidence interval for significant change in individual scores for the youngest participants. Three participants showed better performance (lower SNR-50 score) with DSL v5 Quiet, three showed better performance with DSL v5 Noise, and five showed no significant performance difference between prescriptions.

Figure 3-7 shows mean SNR-50 scores for the DSL v5 Quiet and Noise prescriptions on the BKB-SIN task; error bars represent one standard deviation above and below the mean. The SNR-50 scores were analyzed by a repeated measures analysis of variance with prescription as the within-subjects factor. Results indicated that the main effect of prescription was not significant ($F(1,10) = 0.000$, $p = 0.99$, $\eta^2 = 0.00$).

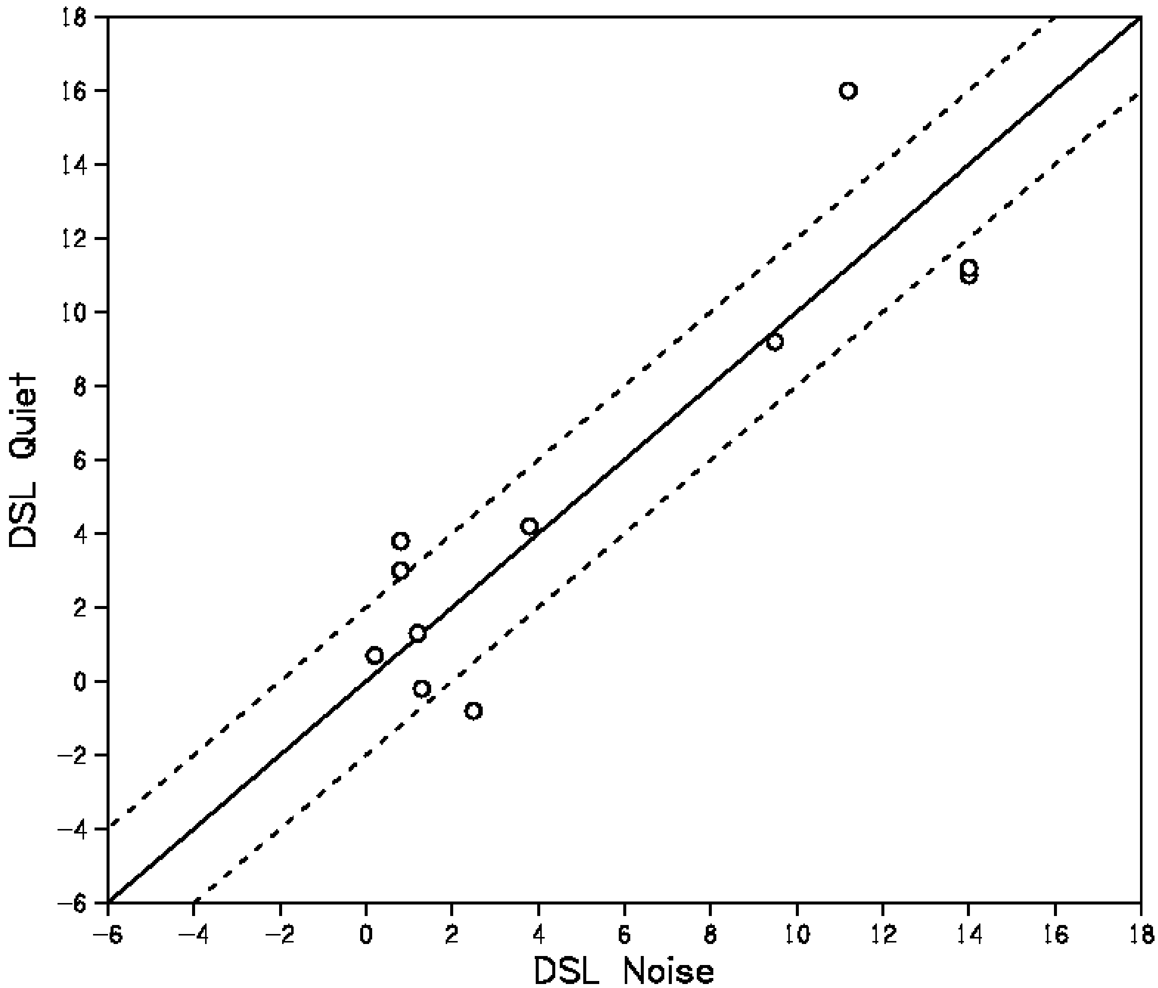

Figure 3-6: Individual scores on the speech-in-noise task (in SNR-50) across prescriptions. Dashed lines indicate the 95% confidence interval for significant change in individual scores.

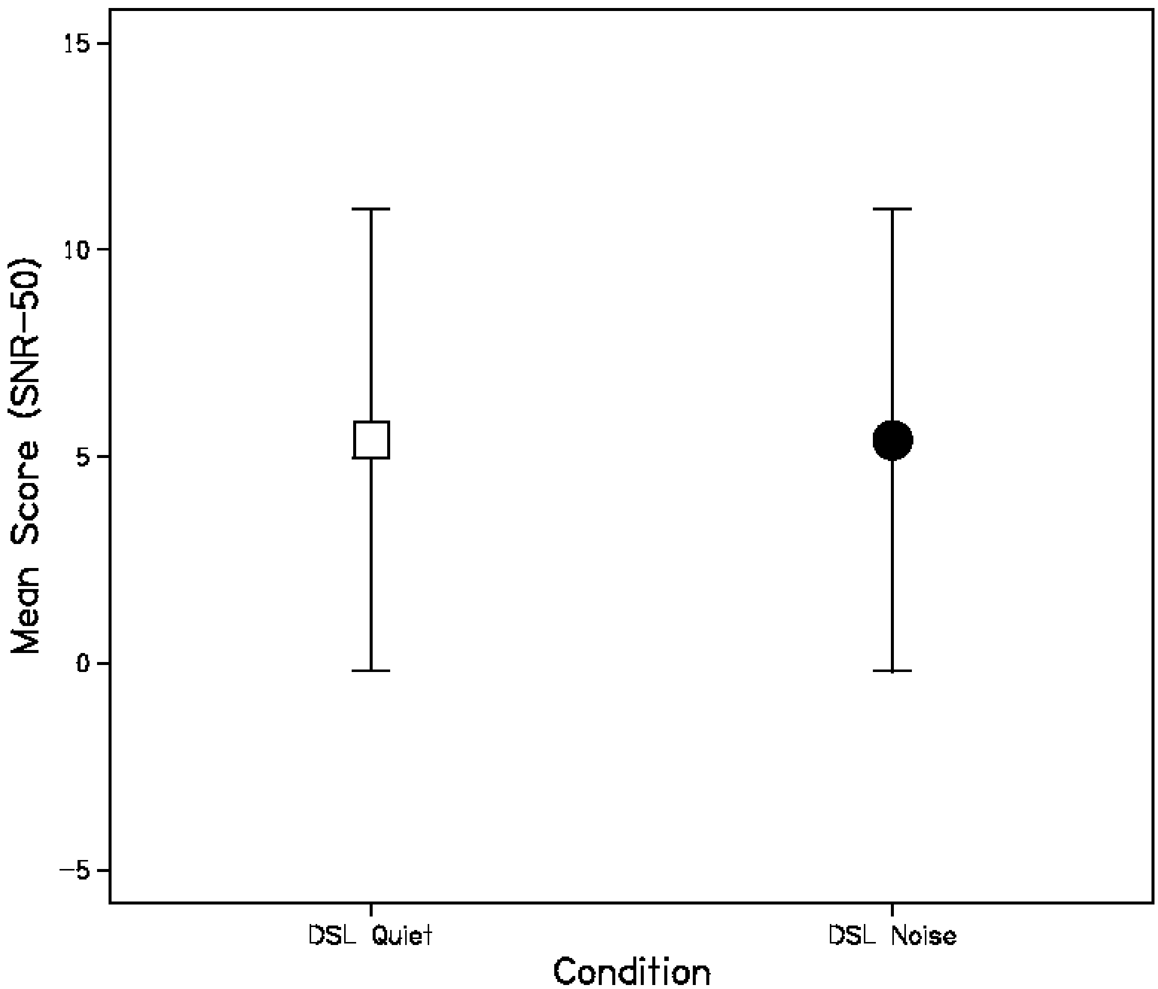

Figure 3-7: Mean BKB-SIN SNR-50 scores by hearing instrument condition. Vertical bars indicate one standard deviation about the mean.

3.7.3 Loudness Perception

Mean loudness ratings for the sentences in quiet and sentences in noise conditions for each level and prescription are shown in Figure 3-8.

Mean loudness ratings were subjected to a repeated measures analysis with level (eight levels), prescription (two levels), and loudness task condition (two levels) as repeated measures factors. The main effect of level was significant ($F(1.66,16.63) = 156.41$, $p < 0.001$, $\eta^2 = 0.94$), indicating higher ratings with increasing input levels. The main effect of loudness task condition was significant ($F(1,10) = 6.91$, $p = 0.02$, $\eta^2 = 0.41$), with lower ratings for the sentences in noise condition than the sentences in quiet condition. The main effect of prescription was not significant ($F(1,10) = 3.96$, $p = 0.08$, $\eta^2 = 0.28$). The interaction effect of level by prescription was not significant ($F(3.05,30.51) = 1.09$, $p =0.38$, $\eta^2 = 0.10$), the interaction effect of level by loudness task condition was not significant ($F(3.65,36.48) = 2.34$, $p = 0.08$, $\eta^2 = 0.19$), and the interaction effect of prescription by loudness task condition was not significant ($F(1,10) = 0.005$, $p = 0.95$, $\eta^2 = 0.00$).

Research has shown that raised or loud speech occurs at approximately 67 dB SPL (Olsen, 1998; Pearsons et al., 1977). In order to specifically address the second research question “does use of the two prescriptions result in different comfort ratings for loud sounds?”, loudness ratings for the input levels from 68 to 80 dB SPL were averaged together to form an overall rating for “loud sounds” for each loudness perception task condition.

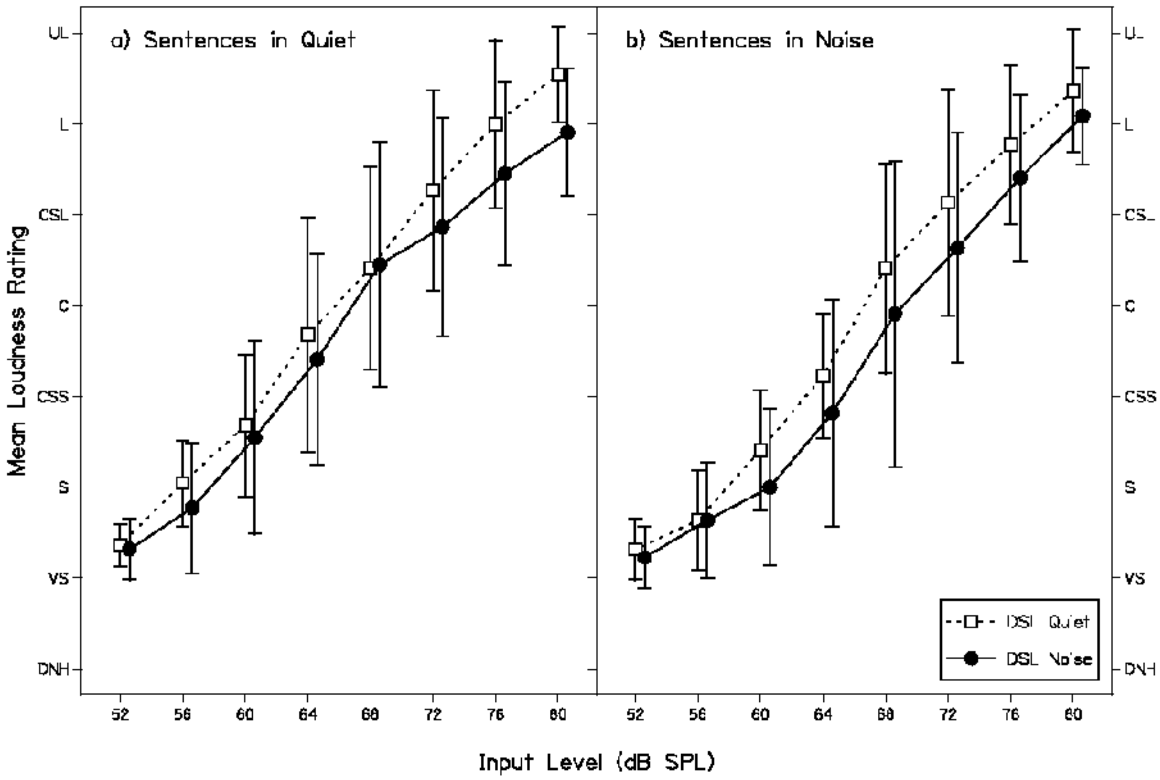

Figure 3-8: Mean loudness ratings by children for both prescriptions for a) sentences in quiet, and b) sentences in noise, where DNH = 'did not hear', VS = "very soft", S = "soft", CSS = "comfortable, but slightly soft", C = "comfortable", CSL = "comfortable, but slightly loud", L = "loud", and UL = 'uncomfortably loud'. Vertical bars indicate one standard deviation about the mean.

The "loud sounds" ratings were subjected to a repeated measures analysis of variance with prescription (two levels) and loudness task condition (two levels) as repeated measures factors. Results indicated that the main effect of prescription was significant ($F(1,10) = 5.93$, $p = 0.04$, $\eta^2 = 0.37$). Mean loudness ratings for the DSL v5 Noise prescription (4.96 ± 1.11) were significantly lower ($t(10) = 2.44$, p = 0.04, $d = 2.16$) than loudness ratings with the DSL v5 Quiet prescription (5.35 ± 0.87). The main effect of loudness task condition was not significant ($F(1,10) = 0.32$, $p=0.23$, $\eta^2 = 0.14$). The interaction effect between prescription and loudness task condition was not significant ($F(1,10) = 0.02$, $p = 0.64$, $\eta^2 = 0.02$).

3.8 Discussion

This study provided a preliminary behavioral evaluation of the DSL v5 Noise prescription, which has to date been a theoretical approach in need of validation. The outcome measurement data presented may assist in the continued development of the DSL Noise prescription towards optimizing the algorithm for use in non-quiet listening situations.

3.8.1 Consonant Recognition

The main effect of level was significant for the consonant recognition task indicating higher scores with the higher input level. Although the overall effect of prescription was not significant there was a significant interaction between test level and prescription, which indicated a decrease in performance at 50 dB SPL using the DSL v5 Noise prescription. These results are similar to the results of Scollie et al. (2010a) where consonant recognition performance with the NAL-NL1 prescription varied with level and performance with the DSL v4.1 prescription did not. This result was expected given the similarity between the DSL v5 Noise and NAL-NL1 prescriptive targets. Both DSL v5 Noise and NAL-NL1 prescribed approximately 10dB less low-frequency gain and 5-10dB less high-frequency gain, relative to DSL v5 Quiet and DSL v4.1, respectively. In general, children performed well with either prescription with an average performance of 79% correct across prescriptions and levels. These scores agree with data published on the UWO-DFD test with children in this age range (Jenstad et al., 1999; Scollie, 2008;

Scollie et al., 2010b). Some children in the study had steeply sloping and profound hearing losses. Previous research has suggested that a child with a greater degree or steeper slope of hearing loss is likely to have poorer speech recognition scores than a child with a lower degree or a shallower slope of hearing loss (Scollie, 2008). It is likely that these larger degrees and steeper slopes of hearing loss contributed to lower average scores relative to the average scores of greater than 85% published by Scollie et al. (2010b). Although consonant recognition performance was lower with the DSL v5 Noise prescription with an input level of 50 dB SPL, it is important to note that the prescription was designed as an alternate prescription for use in noisy or loud environments. As such, in a real-world context the DSL v5 Noise prescription would not be the prescription of choice for a low-level 50 dB SPL input where the audibility maximizing goals of the DSL v5 Quiet prescription would be better suited.

3.8.2 Sentence Recognition in Noise

The main effect of prescription for the BKB-SIN was not significant, indicating no difference in sentence recognition in noise performance between the DSL v5 Quiet and Noise prescriptions. These results are similar to those reported by Scollie et al. (2010b), which indicated no difference in sentence recognition in noise performance between DSL v4.1 and NAL-NL1 prescriptions. This pattern in results may reflect the similarity between DSL v5 Noise and NAL-NL1 prescriptive targets, as described above. Additionally, the DSL v5 Noise prescription was not expected to improve speech recognition scores because it was designed to provide comfort in noisy situations more so than to improve objective performance (Scollie et al., 2005).

3.8.3 Loudness Perception

The main effect of level was significant for the loudness perception task. This result was expected given the 4 dB difference between adjacent input levels used in the task, which existing literature on loudness scaling reports to provide resolution of seven contours (Cox et al., 1997; Cox & Gray, 2001). Although the data in Figure 3-8 show generally lower ratings with the DSL v5 Noise prescription than with the DSL v5 Quiet prescription, the main effect of prescription was not significant across all levels and conditions of the loudness perception task. In general, the loudness data appear similar to those reported in Scollie et al. (2010b); although, the loudness growth functions cannot be directly compared due to the use different ratings scales and input levels between studies. However, both datasets demonstrate two important results related to dynamic range. First, the data in the current study and those of Scollie et al. (2010b) indicate audibility of the lowest input levels across all prescriptions tested. This is important given the necessity of audibility in order for children to perceive and develop language (Pittman & Stelmachowicz, 2000; Stelmachowicz et al., 2000; Stelmachowicz et al., 2007; Stelmachowicz et al., 2001; Stelmachowicz et al., 2004a). Second, the data of Scollie et al. (2010b), demonstrated ratings of "much too loud" for an 80 dB SPL input level for both DSL v4.1 and NAL-NL1 almost equally with both prescriptions. While the current data demonstrate ratings of "uncomfortably loud" for an 80 dB SPL input level with both the DSL v5 Quiet and Noise prescriptions, the average rating with the DSL v5 Noise prescription was lower as shown in Figure 3-8. As seen in Chapter 1, children experience noise levels exceeding 80 dB SPL on a daily basis. Therefore, a prescription that can assist in alleviating aversive loudness may warrant clinical consideration.

There was a significant effect of loudness task condition, which indicated higher loudness ratings when sentences were presented in quiet than when sentences were presented with competing noise. The original purpose of the loudness perception task was to evaluate perceived loudness when competing sound sources were present; it was not expected that the task condition would exert an effect of its own.

It is possible that the participants' experience with the sentences used in the loudness task from the practice trials and the sentence recognition in noise task influenced their loudness rating. The effect of memory influencing loudness perception has been reported in the literature. In a study examining sentence recall and loudness judgments, Jacoby et al. (1988) demonstrated that previous experience with sentences not only made the sentences easier to recall later, but also led participants to report the level of competing noise as being less loud when they had prior experience with sentences. Although the groups of sentences used in the loudness perception task were randomized from trial to trial, the participants heard several of the same sentences used during data collection in the practice sessions. This would have familiarized the children with the sentences and according to the Jacoby et al. (1988) study, may have lead to lower loudness judgments. However, that does not explain why the sentences presented in quiet were rated as being louder than when the same sentences were presented with competing noise. This difference could be attributed to the children rating intelligibility of the sentences rather than the overall loudness of the sentences and noise combined. The same four-talker babble was used for the sentence recognition and loudness perception tasks, and because BKB sentences from the practice lists of the BKB-SIN test materials were used for the loudness perception, the sentence structure was the same across tasks and conditions. Although the participants were instructed not to pay attention to the content of the sentences but only to the overall loudness, it is possible that they interpreted "loudness" as referring to the intelligibility of the sentences, or the level of the sentences over and above the level of the noise. The SNR of the sentences was fixed at 10 dB for sentences in noise condition; however, some children required greater than a 10 dB SNR for 50% correct on the BKB-SIN test as shown in Figure 3-6. This could have led to lower intelligibility, and thus lower ratings corresponding to the amount of signal versus the amount of noise, relative to the sentences presented in quiet even though the overall input levels were matched between conditions. Perhaps it was an interaction between having prior experience and misinterpreting the instructions that lead to the unexpected result of lower loudness ratings with competing signals. Although perplexing, this result has implications for future research regarding loudness judgments with competing signals. Effort should be made to control for task and stimuli familiarity in order to avoid confounds and improve the validity of perception ratings.

The significant main effect of prescription for the "loud sounds" ratings indicated that perceived loudness for input levels of 68 to 80 dB SPL was lower with the DSL v5 Noise prescription than with the DSL v5 Quiet prescription. This result was independent of loudness perception task condition. The lower "loud sounds" ratings reported with the DSL v5 Noise prescription lend support to the potential of a prescriptive approach to alleviate aversive loudness in situations and environments with high-level noise that children experience in their daily lives.

3.8.4 Between-Group Considerations

A primary focus of this study was the external validity of the results. For this reason, participants were tested in their own school environments. However, the size, amount of background noise, and amount of reverberation in the respective test rooms varied between the two sites. Although the differences between rooms precluded analysis of age-related trends or between-group analyses, testing participants in their own school environments supports the representativeness and external validity of data trends.

3.9 Conclusions

The current study addressed three research questions regarding use of the DSL v5 Quiet and Noise hearing instrument prescriptions with a group of school-age children. First, did use of the two prescriptions result in differences in consonant recognition? Although there was a difference between prescriptions for consonant recognition at low levels, scores were good for both prescriptions with an average score of 79% correct across levels, prescriptions, and participants. Second, did use of the two prescriptions result in a difference in sentence recognition in noise? There was no difference in sentence recognition in noise between the two prescriptions. Third, did use of the two prescriptions result in differences comfort ratings for loud sounds? The perceived loudness of loud sounds was rated lower with the DSL v5 Noise prescription than with the DSL v5 Quiet prescription. Overall, speech perception was preserved and aversive loudness was alleviated by the Noise prescription relative to the Quiet prescription, which suggests the DSL v5 Noise prescription may be an effective approach to managing the non-quiet listening needs of children who wear hearing instruments.

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Chapter 4

4 The Effects of Digital Signal Processing Features on Children's Speech Recognition and Loudness Perception

4.1 Introduction

The purpose of the current study was to investigate the effects of hearing instrument digital signal processing (DSP) features on children's performance on tasks of sentence recognition in noise and loudness perception. Directional microphone and digital noise reduction (DNR) technologies were evaluated alone and in combination with two base prescriptions from the Desired Sensation Level (DSL) hearing instrument prescription algorithm, specifically the DSL v5 Quiet and DSL v5 Noise prescriptions.

Difficulty understanding speech-in-noise is a leading cause of listeners' dissatisfaction with hearing instruments (Kochkin, 2007). Real-world, non-quiet listening environments can be divided into two general categories; i) speech amidst background noise, a situation in which understanding speech is a primary goal, and ii) loud environments, a situation in which comfort is a primary goal. There are also cases of overlap between these two categories; for example, there are times that some speech understanding is desired but not at the expense of comfort. As discussed in Chapter 1, non-quiet listening environments can be generally defined in terms of three variable acoustic properties: sound level, signal-to-noise ratio (SNR), and reverberation time (RT). The impacts of these acoustic properties on listening were also discussed in previous chapters. Briefly, the overall level of sound in a given environment can be perceived as aversive at high levels, especially for individuals who wear hearing instruments (Cox & Gray, 2001; Jenstad, Pumford, Seewald, & Cornelisse, 2000; Scollie et al., 2010b). Individuals' ability to understand speech in a given environment is directly related to the SNR present in that environment with speech recognition ability increasing with increasing SNR (Fallon, Trehub, & Schneider, 2000; Fallon, Trehub, & Schneider, 2002; NáběLek & NáběLek, 1994; Neuman, Wroblewski, Hajicek, & Rubinstein, 2010). Speech recognition abilities are inversely related to RT, with speech recognition performance decreasing with increasing RT (Náběelek & Náběelek, 1994; Smaldino, Crandell, Brian, Kreisman, & Kreisman, 2008). These acoustic properties have been demonstrated to interact with the age and hearing status of individuals. In general, children with hearing loss require louder speech signals, higher SNRs, and lower RT than children with normal hearing in order to achieve similar levels of speech recognition performance (Boothroyd, 2008; Elliott, 1979; Fallon et al., 2002; Finitzo-Hieber & Tillman, 1978; Náběelek & Náběelek, 1994; Scollie, 2008; Smaldino et al., 2008).

4.1.1 The DSL Prescriptive Algorithm

The DSL prescriptive algorithm and its evolution with advances in hearing instrument technology were discussed in Chapters 1 and 3. Briefly, the DSL prescription has traditionally been a pediatric-focused fitting method, which has sought to maximize audibility in the prescription of frequency-gain response (Scollie et al., 2005; Seewald, Ross, & Spiro, 1985). DSL version 3.1 focused on optimizing audibility of average-level speech using linear amplification (Seewald et al., 1985). DSL v4.1 was developed with the advent of non-linear amplification in hearing instruments. The goals of the prescription evolved to include targets for a range of inputs above and below average-level speech (Cornelisse, Seewald, & Jamieson, 1995). The most recent version, DSL v5, demonstrates continued evolution of the algorithm by including separate sets of prescriptive targets for congenital and acquired hearing losses, as well as separate prescriptions for use in quiet and noisy environments (Scollie et al., 2005).

Results of a study investigating the effects of the DSL v5 Quiet and Noise prescriptions on children's consonant recognition, sentence in noise recognition, and loudness perception were presented in Chapter 3. The data indicated that use of the DSL v5 Noise prescription resulted in significantly lower loudness ratings for high-level inputs. However, there was no difference in sentence recognition in noise performance between the two prescriptions and consonant recognition performance was poorer at a low input level only with the DSL v5 Noise prescription. These results were in accordance with the goal of the DSL v5 Noise prescription, which was to improve listening comfort in noisy environments more than to improve speech recognition performance (Scollie et al., 2005).

4.1.2 Listening Needs of Children

As discussed previously, maximizing the audibility of speech sounds across input levels is especially important in the prescription of hearing instruments for children (AAA, 2003; CASLPO, 2002; The Pediatric Working Group, 1996); research has shown that children with hearing loss require more audibility (higher sensation levels) and a larger bandwidth in order to perceive and thus develop language (Pittman & Stelmachowicz, 2000; Stelmachowicz, Hoover, Lewis, Kortekaas, & Pittman, 2000; Stelmachowicz et al., 2007; Stelmachowicz, Pittman, Hoover, & Lewis, 2001; Stelmachowicz et al., 2004).

While maximizing audibility of speech sounds in quiet environments is a priority in pediatric hearing instrument prescription, managing children's listening needs in non-quiet environments is also an important consideration. The data presented in Chapter 2 demonstrated the diverse range of listening environments experienced by children in their daily lives. A study by Scollie et al. (2010a) demonstrated children's varied listening needs and preferences across the diverse range of listening environments they encountered. Taken together, the data from these studies highlight the need for clinical management of children's listening needs in non-quiet environments.

Clinical management of children's non-quiet listening needs has to consider both the importance of maintaining speech recognition and of controlling aversive loudness. One approach to managing non-quiet listening is use of a lower gain prescription. The data regarding the ability of a lower gain prescription to reduce aversive loudness ratings is mixed. While the data presented in Chapter 3 indicated a reduction in loudness ratings for loud sounds with use of a lower gain prescription, the data reported by Scollie et al. (2010b) indicated no difference in reported aversive ratings of loud sounds between fittings with DSL v4.1 and a lower gain prescription (NAL-NL1). Although a lower gain approach may assist in reducing the aversiveness of loud sounds, the data presented in Chapter 3 and those of Scollie et al. (2010b) indicated reduced consonant recognition scores at low input levels and no difference in sentence recognition in noise performance with use of a lower gain prescription. These mixed results illustrate the difficulty in balancing the need to maintain speech recognition while reducing aversive experience with loud sounds in the management of non-quiet listening for children.

Modern hearing instruments offer strategies in addition to lower gain prescriptions for managing listening in noise. Features such as directional microphones and DNR can be combined with a base frequency-gain response for managing non-quiet listening.

4.1.3 Directional Microphones

Directional microphones are less sensitive to sounds originating from certain (non-frontal) directions relative to omnidirectional microphones by design (Ricketts, 2000a, 2001, 2005). In hearing instruments, directional microphones are used to improve the SNR delivered to a listener's ear, assuming the signal of interest is in front of the listener and the unwanted noise is not in front of the listener. This has been shown to enhance listeners' ability to understand speech in noise in adult listeners (Amlani, 2001; Bentler, Egge, Tubbs, Dittberner, & Flamme, 2004a; Bentler, Palmer, & Dittberner, 2004b; Bentler, Palmer, & Mueller, 2006; Bentler, Tubbs, Egge, Flamme, & Dittberner, 2004c; Gnewikow, Ricketts, Bratt, & Mutchler, 2009; Hornsby & Ricketts, 2007; Ricketts, 2000a, 2000b, 2001, 2005; Walden, Surr, Cord, & Dyrlund, 2004; Walden et al., 2005).

A common measure of directional hearing instrument benefit is directional advantage (DA), which is the difference in performance on a speech recognition task (measured with SNR) between omnidirectional and directional hearing aids (DA = omnidirectional SNR – directional SNR). The raw measures of SNR that drive the DA score are typically measured as the SNR at which the listener can correctly understand 50% of sentences (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004; Niquette, 2003). Clinically available tests are typically designed with a speech signal (the target, which the listener attempts to repeat correctly) and a competing signal, which may be spectrally-matched noise or a multi-talker babble. This type of test is highly sensitive to DA when the competing signal is placed at non-front locations.

The ability of directional microphones to improve performance on controlled, objective measures of speech-in-noise tests has been well documented in the literature (Amlani, 2001; Bentler et al., 2004a; Bentler et al., 2004b; Bentler et al., 2006; Bentler et al., 2004c; Hawkins & Yacullo, 1984; Hornsby & Ricketts, 2007; Klemp & Dhar, 2008; Ricketts, 2001, 2005; Ricketts & Dahr, 1999; Walden et al., 2005). However, the benefit from and listener preference for directional microphones in real-world evaluations has been less clear. Some studies have shown listener preference for directional microphones in real-world listening situations, especially when noise sources were behind the listener and the speech source was in front of the listener (Ricketts & Mueller, 2000; Ricketts, Henry, & Gnewikow, 2003; Walden et al., 2004), while other studies have reported lack of a distinct difference between directional and omnidirectional microphone configurations in real-world situations (Bentler, 2005; Compton-Conley, Neuman, Killion, & Levitt, 2004; Cord, Surr, Walden, & Dyrlund, 2004; Cord, Surr, Walden, & Olson, 2002; Gnewikow et al., 2009; Walden et al., 2007)

4.1.4 Children's Use of Directional Microphones

In addition to data demonstrating the benefits of directional microphone use with adults, the literature also reports benefit from directional microphones on measures of speech-in-noise performance with children (Gravel, Fausel, Liskow, & Chobot, 1999; Hawkins, 1984; Kuk, Kollofski, Brown, Melum, & Rosenthal, 1999; Ng, Meston, Scollie, & Seewald, 2011; Ricketts et al., 2007). Although benefit has been demonstrated in objective laboratory measures of speech-in-noise performance, this benefit from directional microphones is somewhat dependent on the correct orientation of the listener's head relative to the talker of interest. Studies have shown that children can correctly orient towards a primary talker, at least some of the time; however, the same studies have indicated that the children are almost as likely to orient incorrectly (Ching et al., 2009; Ricketts & Galster, 2008). Although there appears to be a directional advantage when the signal of interest is in front of the listener, there is also clear directional disadvantage when the listener is not facing the source (Ching et al., 2009; Ricketts et al., 2007).

Properties of room acoustics have been shown to interact with directional microphones. Specifically, the DA of directional microphone systems has been shown to decrease with increasing RT (Amlani, 2001; Hawkins & Yacullo, 1984; Leeuw & Dreschler, 1991; Ricketts, 2001; Ricketts & Dahr, 1999; Ricketts & Hornsby, 2003). As discussed in Chapter 2, children experience a wide range of RTs over the course of a school day; this has implications for the efficacy of directional microphones across the non-quiet environments experienced by children in real-world settings.

Recommendations regarding the use of directional microphones in pediatric hearing instrument fitting are mixed. Some bodies recommend against the use of directional microphones with pediatric hearing instrument fittings due to lack of sufficient evidence (AAA, 2003; Foley, Cameron, & Hostler, 2009), others consider directional microphones to be a viable strategy (Bagatto, Scollie, Hyde, & Seewald, 2010; CASLPO, 2002), while others recommend directional microphones for all pediatric hearing instrument fittings because the benefits are thought to outweigh any disadvantages (King, 2010).

4.1.5 Digital Noise Reduction in Hearing Instruments

DNR is a hearing instrument processing feature, which has been employed to address both general categories of non-quiet listening i) speech in background, noise, with the goal of improving speech recognition, and ii) loud situations, with the goal of improving listening comfort and possibly reducing cognitive demand (Bentler & Chiou, 2006; Dillon, 2001; Mueller, Weber, & Hornsby, 2006; Sarampalis, Kalluri, Edwards, & Hafter, 2009). In its most basic form, DNR processing seeks to reduce hearing instrument gain, and thus output, when noise is present (Bentler & Chiou, 2006; Dillon, 2001). Over the last two decades, noise reduction processing has evolved dramatically. Noise reduction first appeared in analog hearing instruments typically in the form of low-frequency filters and gain reduction circuits (Bentler & Chiou, 2006; Levitt, 2001; Van Tasell, Larsen, & Fabry, 1988). Modern DNR algorithms allow for decision making by the processor regarding how noise is defined, which frequency regions are affected, and how much gain reduction to employ in the affected regions (Bentler & Chiou, 2006). A number of DNR approaches have been implemented to address the goal of improved speech recognition in noise, primarily through attempting to improve the SNR of hearing instrument output. Currently, the two most common forms of DNR are variations of spectral subtraction and channel-based gain reduction. In spectral subtraction systems, an estimate of the noise signal is constructed during pauses between words; the estimated noise signal is then subtracted from the overall (speech plus noise) signal either in the time or frequency domain. In channel-based gain reduction systems, the first step is to estimate the SNR in a given frequency band using a signal processing classifier. Generally, steady-state signals are classified as noise and modulated signals are classified as speech. Gain reduction is then applied per-channel according to predetermined SNR rules set by the DNR algorithm (Bentler & Chiou, 2006; Chung, 2004). DNR systems manipulate a variety of processing parameters; for example, the number of channels affected, amount of gain reduction, time constants, and classification schemes can vary between DNR strategies (Chung, 2004). Improving SNR through reduction of competing noise and preservation of the target signal (speech) has proved challenging due to the time variations and spectral overlap of speech and noise signals most often encountered in the real-world listening environments of hearing instrument users.

In general, research has shown no improvement in speech recognition performance with the use of DNR (Bentler & Chiou, 2006; Bentler, Wu, Kettel, & Hurtig, 2008; Dillon, 2001; Hu & Loizou, 2007; Nordrum, Erler, Garstecki, & Dhar, 2006; Ricketts & Hornsby, 2005). Additionally, previous studies have reported decreased speech recognition performance using DNR with both speech-shaped noise (Van Tasell et al., 1988) and multi-talker babble (Jamieson, Brennan, & Cornelisse, 1995; Sarampalis et al., 2009) as competing signals. The Van Tasell et al. (1988), Jamieson et al. (1995), and Sarampalis et al. (2009) studies each evaluated advanced noise reduction algorithms for their time, which did not yet exist within hearing instruments. Although these studies evaluated cutting-edge technology, all three studies also demonstrated negative results with use of the DNR tested. These studies demonstrate the need for continued DNR development in order to achieve improvements in speech recognition.

While improving speech recognition with DNR has not been successful, the use of DNR in hearing instruments has been shown to provide benefit in terms of listening comfort and preference (Bentler & Chiou, 2006; Bentler et al., 2008; Mueller et al., 2006; Ricketts & Hornsby, 2005). These findings are consistent with the known properties of DNR processing, which affect output level but not overall SNR (Bentler & Chiou, 2006; Dillon, 2001; Levitt, 2001).

4.1.6 Children's Use of Digital Noise Reduction

Previous research demonstrates potential for DNR to degrade speech perception (Jamieson et al., 1995; Sarampalis et al., 2009; Van Tasell et al., 1988); DNR may degrade speech perception by altering the spectral content of a signal and more specifically high-frequency content (Jamieson et al., 1995). Children are less resilient to degraded speech signals than adults and may need more high-frequency audibility than adults in order to perceive speech sounds (Scollie, 2008; Stelmachowicz et al., 2004). For these reasons, there has been a recommendation against provision of DNR processing in pediatric hearing instrument fittings until more data demonstrating benefit without detriment to speech perception become available (AAA, 2003; Foley et al., 2009). However, while research examining the effects of DNR on children's speech perception has demonstrated no effective improvement in speech-in-noise performance, the use of DNR in children's hearing instruments does not appear to decrease performance (Pittman, 2011; Stelmachowicz et al., 2010). These results suggest that clinical recommendations regarding provision of DNR in pediatric fittings could be reconsidered.

4.1.7 Use of Directional Microphones and Digital Noise Reduction in Combination

Studies investigating the use of directional microphones in combination with DNR have shown similar results to those of the technologies used independently. In general, performance on objective measures of speech recognition is similar with hearing instruments incorporating directional microphones alone or in combination with DNR (Nordrum et al., 2006; Peeters, Kuk, Lau, & Keenan, 2009; Ricketts & Hornsby, 2005) and the addition of DNR has resulted in improvements in subjective measures of listening comfort (Peeters et al., 2009; Ricketts & Hornsby, 2005) . These results suggest that directional microphones may offer the most improvement in speech understanding while

DNR processing may offer more improvement for listening comfort and reduced listening effort in the presence of noise.

To date, there are no known studies investigating the combination of processing features such as directional microphones and DNR with specific frequency-gain responses in order to achieve the most benefit in terms of both speech recognition and loudness perception.

4.2 Rationale for Current Study

Most current pediatric hearing instrument prescription guidelines do not offer recommendations for non-quiet environments (AAA, 2003; Bagatto et al., 2010; CASLPO, 2002; Foley et al., 2009). Although there are no current recommendations for noise management in pediatric hearing instrument fittings, children have demonstrated a desire for amplification options that reduce listening levels in loud, noisy, or reverberant environments (Scollie et al., 2010a).

Modern hearing instruments offer a number of options to manage non-quiet listening such as: frequency-gain shaping, directional microphones, digital noise reduction, and the available combinations of these technologies. Although there is substantial literature regarding adult use of these strategies alone and in combination, there has been less investigation of their effects in children – an evaluation of children's performance with these available non-quiet management options is warranted.

4.3 Research Questions

The current study addressed two research questions targeting the two general categories of non-quiet listening. First, does the use of a prescribed frequency-gain response, directional microphone, DNR, or a combination result in better speech-in-noise recognition? Second, does the use of a prescribed frequency-gain response, directional microphones, DNR, or a combination result in differences in comfort ratings for loud sounds? The experimental design used to address these questions is summarized in Appendix B.

4.4 Methods

4.4.1 Participants

Ten children were recruited to participate in the study. Participants included four children from an elementary school self-contained class for the deaf and hard of hearing, and six children from a high school hearing resource class. The average age of the elementary school children was 8.71 years (range: 8.0 to 9.75 years); the average age of the high school children was 15.18 (range: 13.83 to 17.58 years). Both schools were located in London, Ontario and are a part of the Thames Valley District School Board's Deaf and Hard of Hearing Program. All participants were full-time hearing instrument users with stable, bilateral, congenital sensory-neural hearing losses.

Data from previous research evaluating children's performance on the BKB-SIN with omnidirectional and directional microphones (Ng et al., 2011) were used for sample size estimation. Results indicated that a total sample size of six individuals would be sufficient to detect the hypothesized effect of a two-level within-subjects independent variable 81.9 percent of the time using a 0.05 alpha level (Lee, 2004).

4.4.1.1 Hearing Threshold Levels

Hearing threshold levels were measured by the participants' clinical audiologists within six months prior to study enrollment. Hearing losses ranged from moderate to profound degrees; audiometric thresholds for the left and right ears of all participants are shown in Figure 4-1.

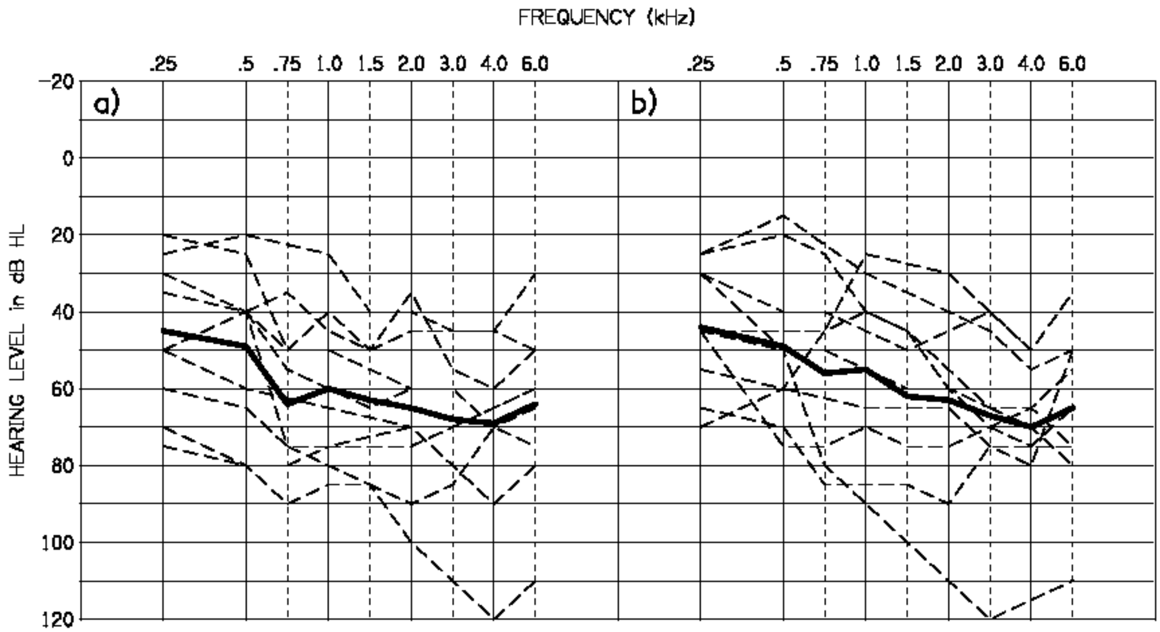

Figure 4-1: Audiometric thresholds for all subjects. Panel a shows left ear thresholds, panel b shows right ear thresholds; bold lines are average audiograms.

4.5 Hearing Instrument Fitting Procedure

All participants were fitted with Phonak Versata Art SP behind-the-ear hearing instruments. Fitting procedures followed recommended protocols and were described in detail in Chapter 3. Briefly, all hearing instruments were fitted using measures of aided speech, in a verification system that allowed simulated real-ear measurement (sREM). Hearing instruments were fit using individual ear canal acoustic measurements in the form of Real-Ear to Coupler Difference (RECD) measurements according to recommended procedures (Bagatto et al., 2005).

DSL v5 Quiet prescription targets were generated by the verification system and custom software was used to generate targets for the DSL v5 Noise prescriptions, using the participants' audiometric thresholds and RECDs. DSL v5 Quiet prescriptive targets were calculated for input levels of 55, 65, and 70 dB SPL. DSL v5 Noise prescriptive targets were calculated for input levels of 55, 65, and 75 dB SPL.

Participants wore the hearing instruments for a period of two weeks prior to data collection in order to acclimate to their new devices. Middle ear status was monitored by immittance testing with a portable tympanometer at the beginning of each session

4.5.1 DSP Features

Following the fitting of the omnidirectional programs of each hearing instrument (see Chapter 3 for details) directional microphones and DNR were enabled by activating the feature within the fitting software with the given base prescription fitting; frequency-gain response was not adjusted further after enabling a given feature. The directional microphone condition used the "fixed directional" setting within the fitting software, which put the hearing instruments into a fixed cardioid polar pattern. The DNR condition used the "strong" setting of "NoiseBlock" processing within the fitting software. NoiseBlock is a channel-based gain reduction system that reduces gain in channels with lower estimated SNR. SNR estimates are based on the amount of modulation detected in the input signal per channel. SNR estimates are lower in channels with lower amounts of modulation, which results in higher degrees of gain reduction in those channels. The combined condition used the “fixed directional” and “strong” NoiseBlock settings both enabled.

In the following figures and tables, hearing instrument conditions are annotated as follows: No DSP = base prescription alone with an omnidirectional microphone, DIR = directional microphone enabled, DNR = digital noise reduction enabled, DIR+DNR = both directional microphones and DNR enabled.

Due to their design, directional microphones result in a reduction of low-frequency output relative to that of an omnidirectional microphone (Ricketts & Henry, 2002; Ricketts, 2001). Figure 4-2 shows the effects of the DSP features and their combination on frequency response. The figure shows the difference in hearing instrument output, by frequency, for a speech signal at three input levels averaged across all study participants. No manual gain compensation was applied to the directional microphone fittings. However, it is possible that the fitting software imposed adjustments to the frequency response of the hearing instruments when the directional microphone was enabled. The degree of low-frequency output reduction, relative to the omnidirectional microphone setting, appeared to be level dependent and was less than the 6 dB per octave expected from the data of Ricketts and Henry (2002). Additionally, there appeared to be a level dependent increase in mid-frequency output when the directional microphone was enabled. The difference in output was less than ± 3 dB across frequencies and input levels.

The amount of gain reduction applied by DNR depends on characteristics of the input signal and the classification scheme of the DNR algorithm. Most DNR algorithms attempt to maintain audibility of speech and therefore do not typically impose much if any gain reduction for speech and speech-like inputs. Figure 4-3 shows the difference in hearing instrument output between the “Strong” and “Off” NoiseBlock settings for speech and pink noise signals generated by the Audioscan RM500SL at three input levels. The amount of gain reduction ranged from approximately 0 dB for speech and from 5 to 15 dB for pink noise, across frequencies, with more gain reduction applied at the higher input levels tested.

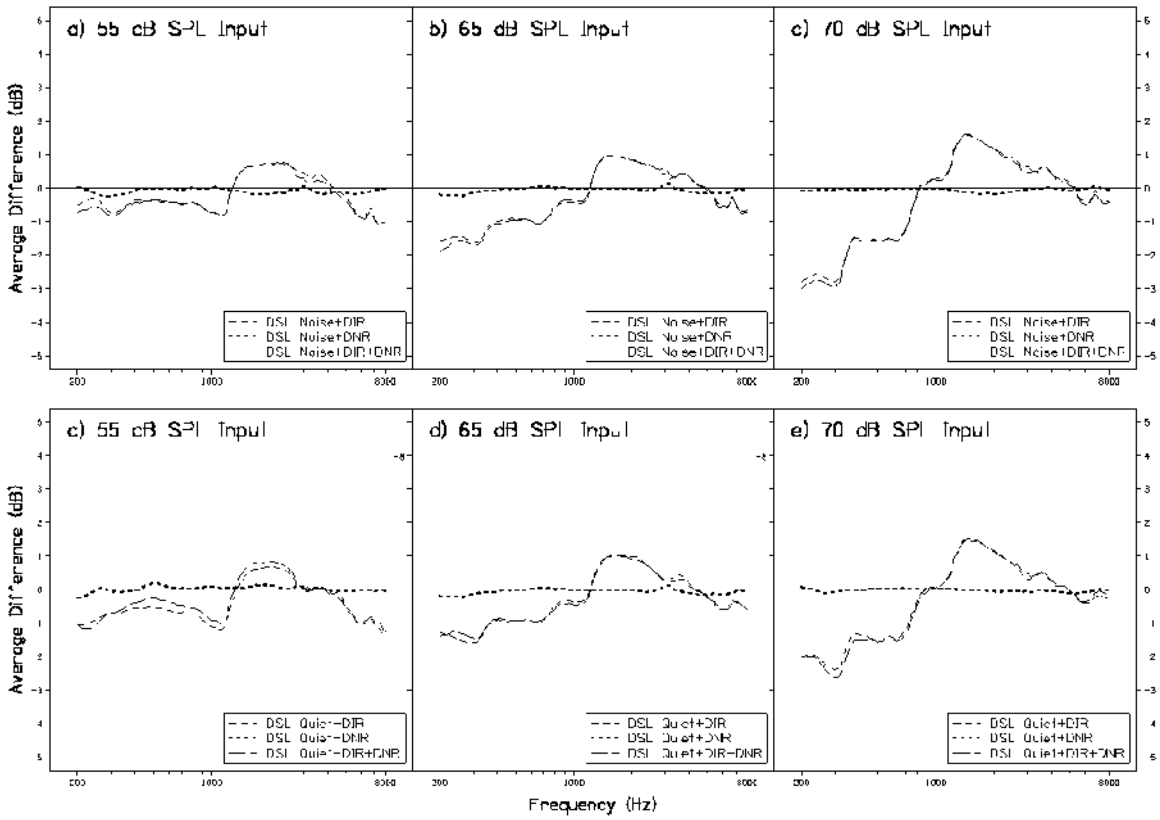

Figure 4-2: Frequency response differences for the various DSP features relative to the DSL Quiet prescription with omni-directional microphone as reference. Panel a, b, and c show differences for 55, 65, and 70 dB SPL input levels, respectively, for the DSL v5 Noise base prescription. Panel c, d, and e show differences for 55, 65, and 70 dB SPL input levels, respectively, for the DSL v5 Quiet base prescription.

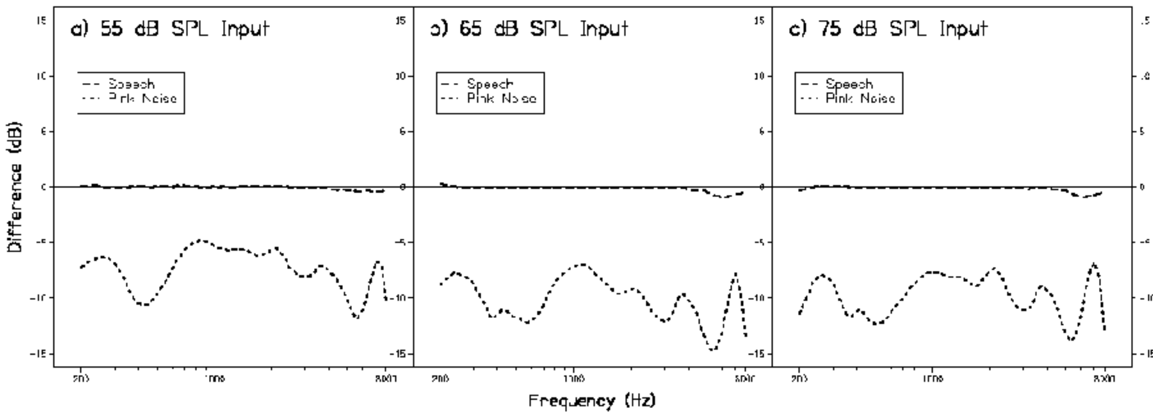

Figure 4-3: Frequency response difference between the "Strong" and "Off" settings of the DNR feature for speech and pink noise at a) 55, b) 65, and c) 75 dB SPL input levels.

Figure 4-4 shows the difference in hearing instrument output between the “Strong” and “Off” NoiseBlock settings for Auditec four-talker babble (Auditec of St. Louis, 1971) and pink noise signals, at 75 dB SPL, measured with a Brüel and Kjær measurement system and SpectraPlus software (Pioneer Hill Software LLC, 2008). The amount of gain reduction was approximately 3 dB in the low frequencies for the four-talker babble and ranged from 5 to 10 dB for pink noise across frequencies.

4.5.2 Equipment

A test system comprised of a laptop running custom software and a custom-built external hardware interface was used to control the presentation of test stimuli and record subject responses for the outcome measures. A detailed description of the experimental set up was presented in Chapter 3. Briefly, target stimuli were presented through a tripod-mounted powered speaker positioned at 0° relative to the test position. The competing stimulus was presented through an Omnipanel speaker system positioned at 180° relative to the test position. The speakers were positioned approximately 6 m apart with the participant seated between them (approximately 3 m from each speaker). The test system was set up in a classroom at both the elementary and high school for data collection.

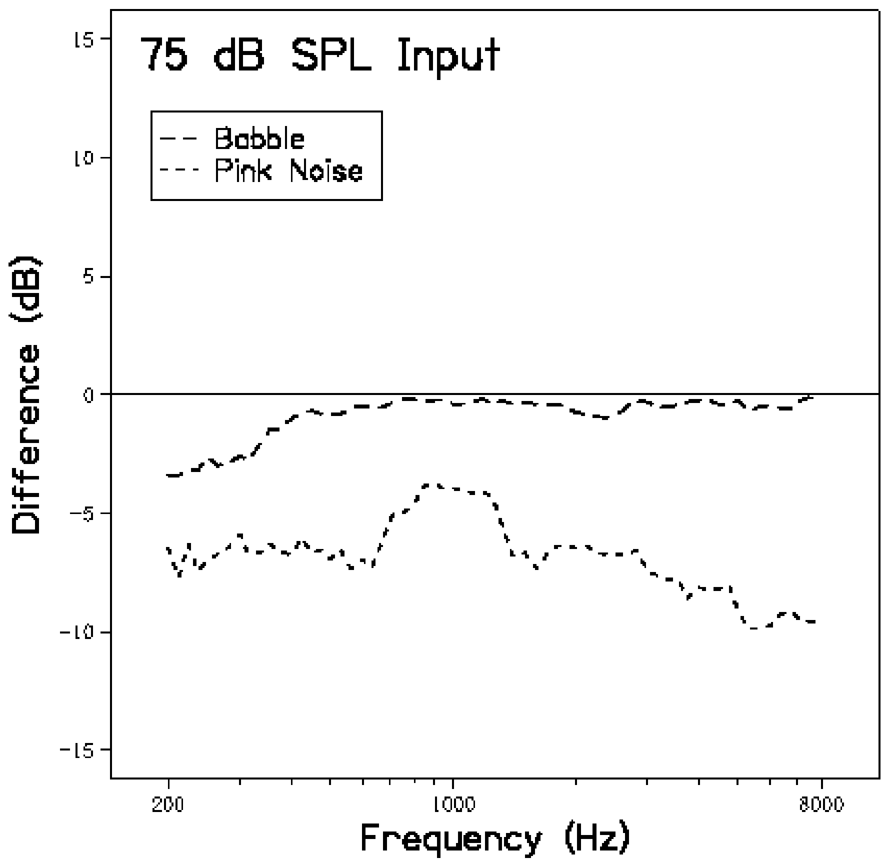

Figure 4-4: Frequency response difference between the "Strong" and "Off" settings of the DNR feature for four-talker babble and pink noise signals at a 75 dB SPL input level.

4.5.3 Outcome Measures

4.5.3.1 Sentence Recognition in Noise

As described in Chapter 3, the Bamford-Kowal-Bench Speech in Noise test (BKB-SIN; Niquette, 2003) was administered through the computer controlled system according to the test manual's instructions (Etymotic Research, 2005). Briefly, three list pairs were presented for each condition using the split tracks from the test BKB-SIN CD. The signal level was calibrated daily to 70 dB SPL for each speaker at the test position with a tolerance of ±0.5 dB. The order of prescription was counter-balanced across subjects.

4.5.3.2 Loudness Perception

The Contour Test of Loudness Perception (Cox, Alexander, Taylor, & Gray, 1997; Cox & Gray, 2001) was administered through the computer controlled system according to the methods of Cox and Gray (2001) as described in Chapter 3. Briefly, two conditions were tested: i) sentences in quiet and; ii) sentences in noise. Materials from the BKB-SIN were used for both conditions. In both conditions, stimulus presentation began at 52 dB SPL and ascended in 4 dB steps to a maximum level of 80 dB SPL, then descended in 4 dB steps back down to 52 dB SPL. For the sentences in noise condition, the SNR of the sentences relative to the babble was fixed at +10 dB. Loudness perception categories spanned 8 levels (0 = did not hear, 1 = very soft, 2 = soft, 3 = comfortable but slightly soft, 4 = comfortable, 5 = comfortable but slightly loud, 6 = loud but okay, 7 = uncomfortably loud). The task automatically reversed direction after the presentation level reached 80 dB SPL or as soon as 'uncomfortably loud' was selected, whichever happened first. The perception categories were displayed as text on a computer monitor and participants were asked to select their rating by clicking the elected category with a computer mouse. As described in Chapter 3, the youngest participants were given a sheet of paper with pictures representing the perception categories in order to facilitate the task. The order of prescription and loudness perception conditions were counter-balanced across participants.

As detailed in Chapter 3 loudness ratings from the ascending and descending runs were averaged together to create a single loudness rating for each input level for analysis. In instances where the participant selected 'uncomfortably loud' before presentation at 80 dB SPL, thus reversing the direction of the task, missing data were replaced with 'uncomfortably loud' ratings

4.5.3.3 Test Administration Details

Children were blinded to conditions. The researcher was not blind to conditions; however, for the computer-administered task (loudness perception), the researcher was not involved in the scoring of the data and thus the effect of blinding was achieved. For the BKB-SIN, the researcher scored the task and thus blinding was not achieved. Test order was kept constant, with test order effects addressed by counter-balancing the sequence of hearing instrument conditions across participants.

4.6 Results

Following the recommendation of Max and Onghena (1999), the Greenhouse-Geisser correction was used to adjust degrees of freedom universally in all repeated measures analyses below in order to control for any potential violations of the sphericity assumption.

4.6.1 Sentence Recognition in Noise

SNR-50 scores averaged across three list pairs in each prescription and across subject ranged from -4.5 to 16.0 dB. Table 4-1 shows significant individual differences between conditions relative to the DSL v5 Quiet prescription alone. A change in SNR-50 score of ±2 dB represents a significant difference based on the 95% confidence interval for significant change using three list pairs for the age group of the study participants according to the BKB-SIN manual (Etymotic Research, 2005). In this table "+" indicates better performance (lower SNR-50) score, "-" indicates poorer performance (higher SNR-50). Individual participant data are presented in order of ascending four-frequency pure-tone average. A high proportion of subjects demonstrated improved sentence recognition in noise scores with use of a directional microphone, regardless of base prescription.

Table 4-1: Sentence Recognition in Noise Performance Relative to Reference Condition

	Participant number										
Condition	1	2	3	4	5	6	7	8	9	10	No. of participants with significant change
DSL N	+		+	+	-					-	3 + 2 -
DSL Q + DNR	+			+	-	-					2 + 2 -
DSL N + DNR				+	-			+			2 + 1 -
DSL Q + DIR	+	+	+	+		+	+	+	+	+	9 + 0 -
DSL N + DIR	+	+	+	+	+	+	+	+	+		9 + 0 -
DSL Q + DIR + DNR	+	+	+	+		+	+	+	+	+	9 + 0 -
DSL N + DIR + DNR	+	+	+	+	+	+	+	+	+		9 + 0 -

Note. + = change in score exceeded 95% confidence interval in the positive direction

- = change in score exceeded 95% confidence interval in the negative direction

Participants are presented in ascending order of four-frequency pure-tone average hearing threshold level.

Figure 4-5 shows mean SNR-50 scores for each hearing instrument condition; error bars represent one standard deviation above and below the mean. SNR-50 scores were analyzed by a repeated measures analysis of variance with prescription (two levels) and DSP (four levels) as within-subjects factors. Results indicated that the main effect of prescription was not significant ($F(1,9) = 0.22$, $p = 0.65$, $\eta^2 = 0.02$). The main effect of DSP was significant ($F(1.59,14.31) = 40.87$, $p = 0.001$, $\eta^2 = 0.82$). The interaction effect between prescription and DSP was not significant ($F(2.42,21.73) = 0.97$, $p = 0.41$, $\eta^2 = 0.10$). Results of Bonferroni post-hoc testing indicated that performance was significantly better (lower SNR-50) with a directional microphone alone than with no DSP features enabled ($t(9) = 7.07$, p < 0 .001, $d = 8.51$) or with DNR alone ($t(9) = 7.76$, p < 0.001, $d = 8.52$). Performance was better with a directional microphone and DNR combined than with no DSP features enabled ($t(9) = 6.28$, p < 0.001, $d = 6.58$) or with DNR alone ($t(9) = 6.60$, p < 0.001, $d = 7.73$). The difference between performance with a directional microphone alone and combined with DNR was not significant (t(9) = 2.76, p = 0.02, $d = 6.03$). Overall the best average performance was obtained with directional microphone use.

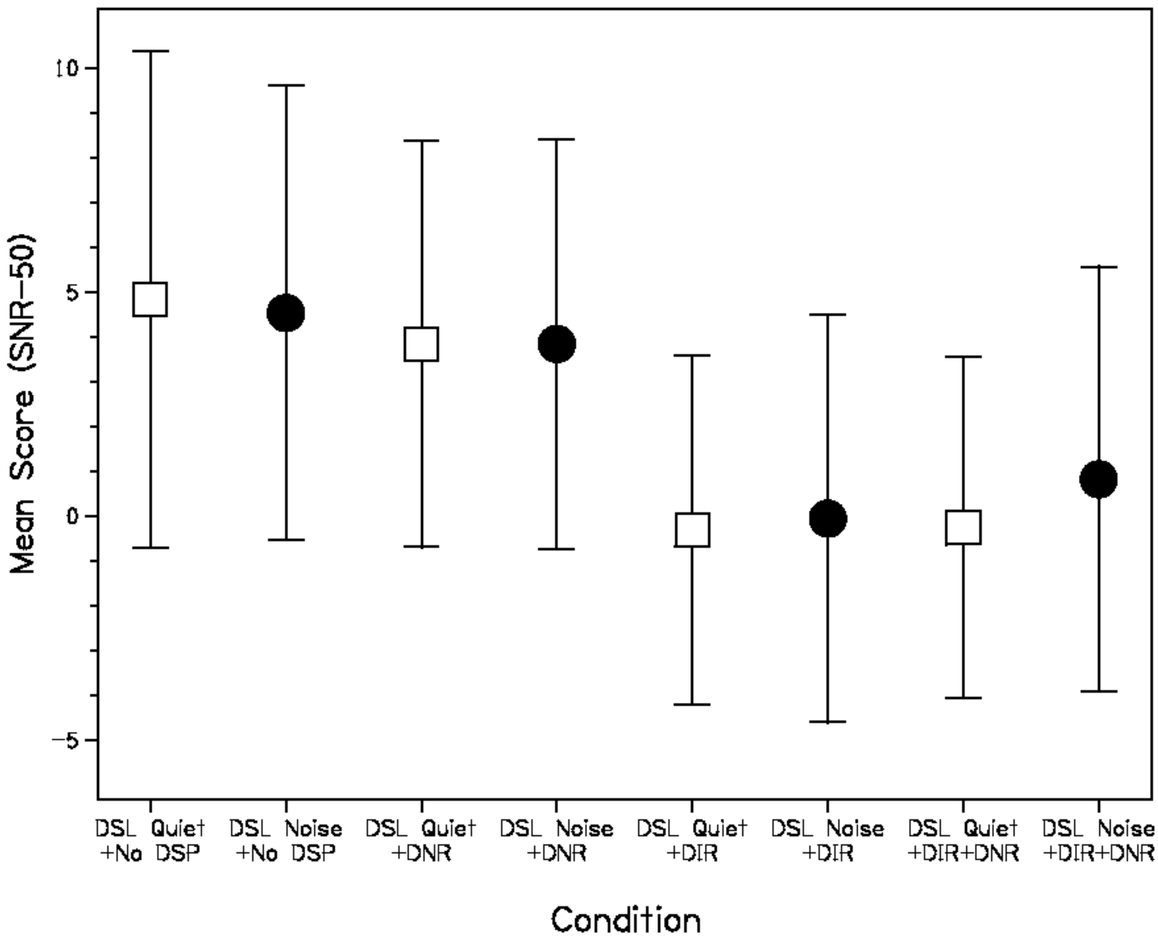

Figure 4-5: Mean BKB-SIN SNR-50 scores by hearing instrument condition. Vertical bars indicate one standard deviation about the mean.

4.6.2 Loudness Perception

Mean loudness perception ratings for the sentences in quiet and sentences in noise loudness perception tasks for each level and hearing instrument condition are shown in Figure 4-6.

Mean loudness perception ratings were subjected to a repeated measures analysis with level (eight levels), prescription (two levels), loudness task condition (two levels), and DSP (four levels) as repeated measures factors. The main effect of level was significant ($F(1.89,17.00) = 231.99$, $p < 0.001$, $\eta^2 = 0.96$), indicating higher loudness ratings with higher input levels. The main effect of prescription was significant ($F(1,9) = 16.09$, $p = 0.003$, $\eta^2 = 0.64$), indicating lower loudness ratings with the DSL v5 Noise prescription than with the DSL v5 Quiet prescription. The main effect of loudness task condition was significant ($F(1,9) = 31.81$, $p < 0.001$, $\eta^2 = 0.78$), indicating lower loudness ratings in the sentences in noise condition than in the sentences in quiet condition. The main effect of DSP was not significant ($F(2.339,21.06) = 1.55$, $p = 0.22$, $\eta^2 = 0.15$). The interaction effect of level by loudness task condition was significant ($F(3.49,31.37) = 3.70$, $p < 0.001$, $\eta^2 = 0.48$). No other interaction effects were significant.

Mean loudness ratings were averaged across both prescriptions and levels of DSP for each presentation level to investigate the significant interaction effect between level and loudness perception task condition. Results of Bonferroni post-hoc testing (Table 4-2) indicated significantly lower loudness ratings in the sentences in noise condition at 56, 60, 64, 68, and 72 dB SPL. The difference between ratings was not significant at 52, 76, or 80 dB SPL. The mean loudness ratings collapsed across prescriptions and levels of DSP are shown in Figure 4-7.

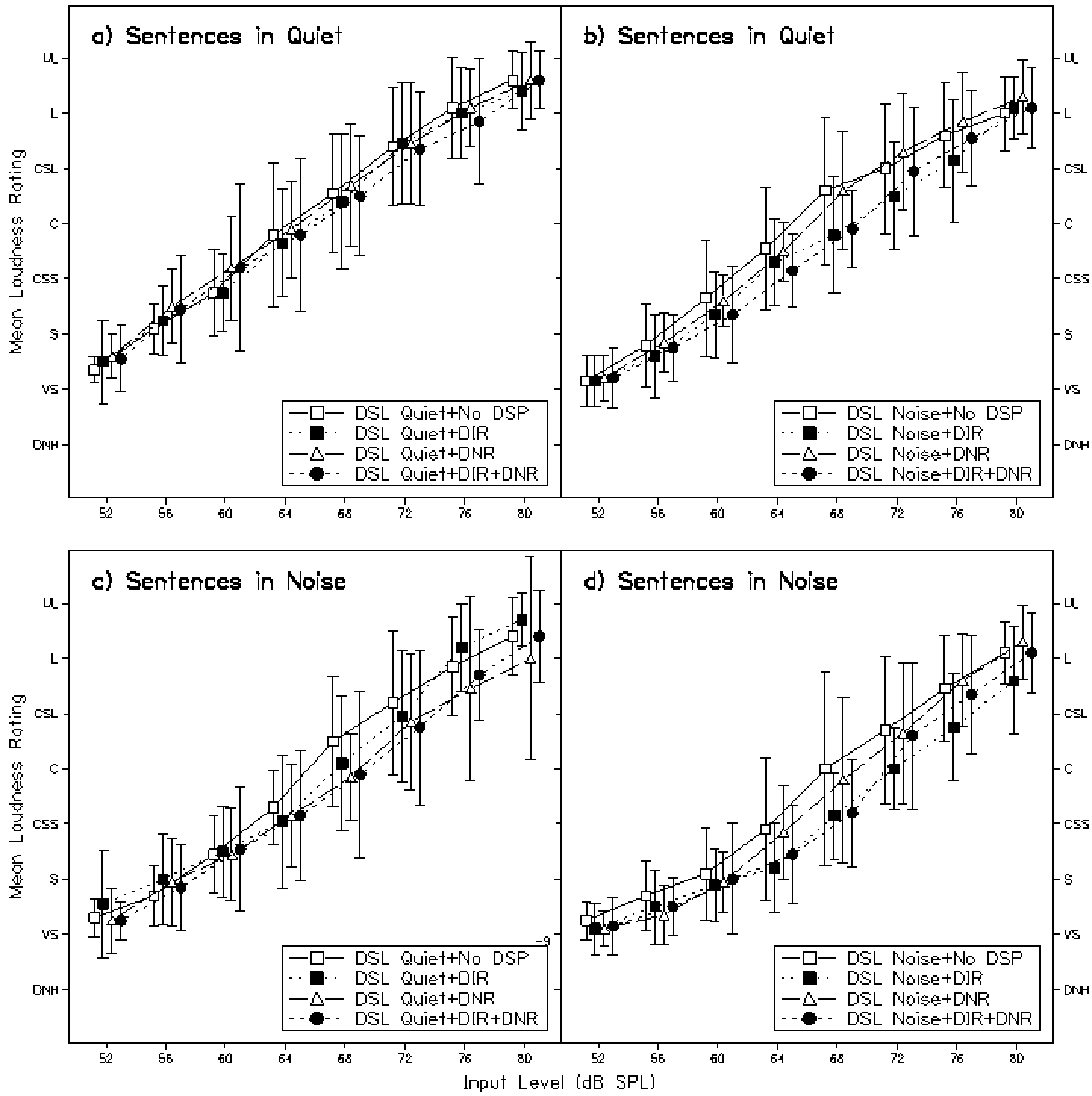

Figure 4-6: Mean loudness ratings by children for each DSP feature for a) sentences in quiet with the DSL v5 Quiet base prescription; b) sentences in quiet with the DSL v5 Noise base prescription; c) sentences in noise with the DSL v5 Quiet base prescription; d) sentences in noise with the DSL v5 Noise base prescription, where DNH = 'did not hear', VS = "very soft", S = "soft", CSS = "comfortable, but slightly soft", C = "comfortable", CSL = "comfortable, but slightly loud", L = "loud", and UL = 'uncomfortably loud'. Vertical bars indicate one standard deviation about the mean.

Table 4-2: Mean Loudness Rating Differences Between Loudness Perception Task Conditions

Level	Mean sentences in quiet loudness rating	Mean sentences in noise loudness rating	Difference	*t*	df	*p*	*d*
52	1.34	1.25	0.09	1.39	9	0.20	1.07
56	2.04	1.70	0.34	7.04	9	< 0.001	10.16
60	2.73	2.25	0.48	5.65	9	< 0.001	6.85
64	3.58	2.91	0.68	5.85	9	< 0.001	6.09
68	4.38	3.86	0.53	4.87	9	0.001	7.34
72	5.18	4.77	0.41	3.94	9	0.003	5.75
76	5.78	5.61	0.16	1.87	9	0.95	2.26
80	6.34	6.28	0.06	1.6	9	0.14	2.71

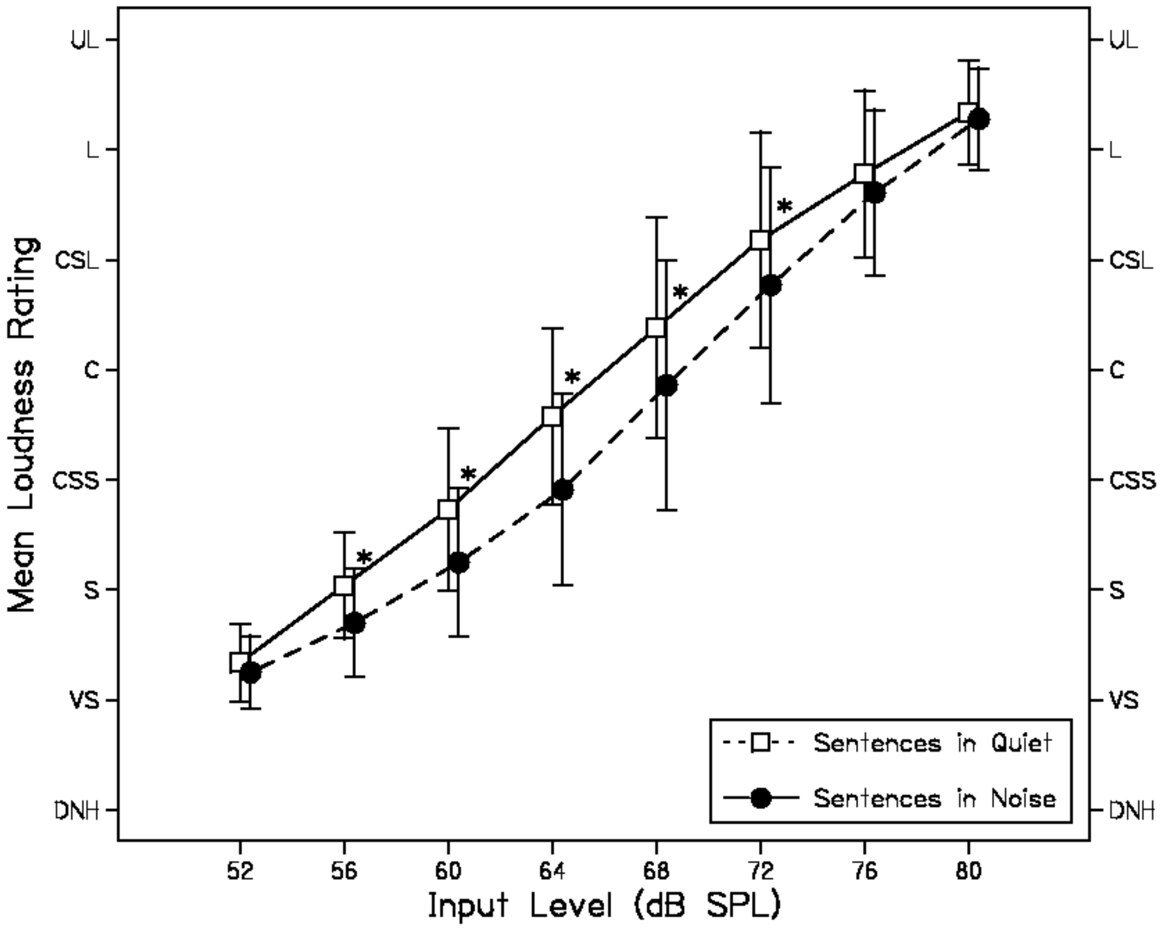

Figure 4-7: Mean loudness ratings by children collapsed across prescription and DSP features, where DNH = 'did not hear', VS = "very soft", S = "soft", CSS = "comfortable, but slightly soft", C = "comfortable", CSL = "comfortable, but slightly loud", L = "loud", and UL = 'uncomfortably loud'. Vertical bars indicate one standard deviation about the mean. Asterisks mark test levels with significant loudness differences between conditions.

To specifically address the second research question: "does the use of directional microphones, DNR, or a combination result in differences in comfort ratings for loud sounds?" the method described in Chapter 3 was used to create a modified loudness rating. Specifically, loudness ratings for input levels from 68 to 80 dB SPL were averaged together to form a single "loud sounds" rating for each loudness perception task condition. The average rating for "loud sounds" in both loudness perception conditions and the four DSP conditions for each base prescription are shown in Figure 4-8.

The "loud sounds" ratings were subjected to a repeated measures analysis with prescription (two levels), DSP (four levels), and loudness task condition (two levels) as repeated measures factors. Results indicated that the main effect of prescription was significant ($F(1,9) = 15.65$, $p = 0.003$, $\eta^2 = 0.64$), indicating lower loudness ratings with the DSL v5 Noise prescription than with the DSL v5 Quiet prescription. The main effect of DSP was significant ($F(2.65,23.88) = 6.44$, $p = 0.003$, $\eta^2 = 0.42$), indicating a difference between loudness ratings when DSP features were enabled. The main effect of loudness task condition was significant ($F(1,9) = 18.53$, $p = 0.002$, $\eta^2 = 0.67$), indicating lower loudness ratings in the sentences in noise condition than in the sentences in quiet condition. There were significant interaction effects between prescription and DSP ($F(2.48,22.34) = 3.305$, $p = 0.046$, $\eta^2 = 0.27$) and between prescription and loudness perception condition ($F(1,9) = 5.97$, $p = 0.04$, $\eta^2 = 0.40$). The interaction effect between DSP and loudness perception condition was not significant ($F(2.48,22.35) = 0.495$, $p = 0.69$, $\eta^2 = 0.05$).

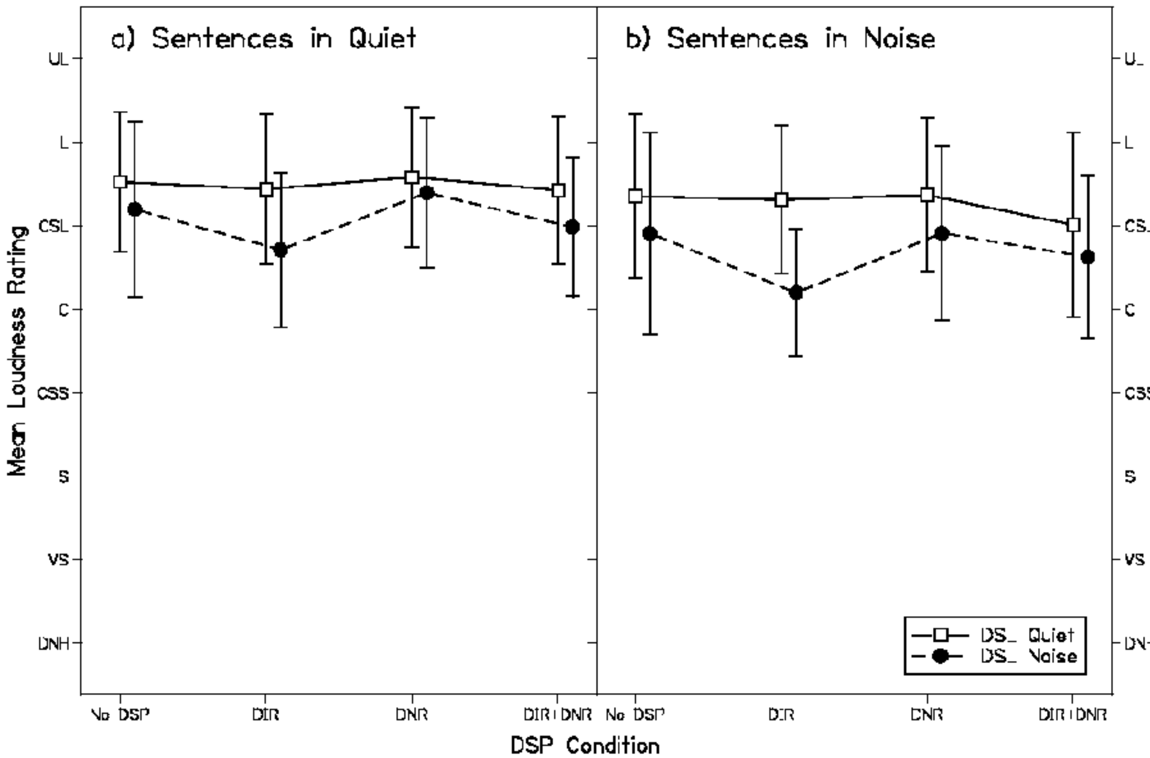

Figure 4-8: Mean loudness ratings for "loud sounds" (68-80 dB SPL input levels) across conditions of the loudness task, DSP, and base prescription, where DNH = 'did not hear', VS = "very soft", S = "soft", CSS = "comfortable, but slightly soft", C = "comfortable", CSL = "comfortable, but slightly loud", L = "loud", and UL = 'uncomfortably loud'. Vertical bars indicate one standard deviation about the mean.

Two sets of post-hoc comparisons were performed to investigate the significant interaction effect between prescription and DSP. In the first set of comparisons, "loud sounds" ratings were collapsed across loudness perception task conditions and each unique combination of prescription and DSP was compared to a reference condition, which was the DSL v5 Quiet prescription with no DSP features enabled. Results of Bonferroni post-hoc analysis indicated that ratings for "loud sounds" were significantly lower with the DSL v5 Noise prescription combined with a directional microphone than with the reference condition ($t(9) = 5.56$, $p < 0.001$, $d = 3.97$); all other comparisons were not significant.

In the second set of comparisons, each level of DSP was compared between the two base prescriptions, collapsed across loudness perception task conditions. Results of Bonferroni post-hoc analysis indicated that loudness ratings with DSL v5 Noise were significantly lower than with DSL v5 Quiet when both prescriptions were paired with a directional microphone ($t(9) = 5.84$, $p < 0.001$, $d = 4.42$); all other comparisons were not significant.

To investigate the significant interaction effect between prescription and loudness perception task condition, "loud sounds" ratings were collapsed across DSP conditions and post-hoc comparisons between each combination of prescription and loudness task condition were performed. Results of Bonferroni post-hoc analysis indicated that loudness ratings with the DSL v5 Noise prescription varied with the loudness perception task condition, with lower ratings in the sentences in noise condition than in the sentences in quiet condition ($t(9) = 6.39$, $p < 0.001$, $d = 13.33$). Loudness ratings with the DSL v5 Quiet prescription did not vary with loudness perception task condition ($t(9) = 2.38$, $p = 0.04$, $d = 3.05$). Additionally, loudness ratings with the DSL v5 Noise prescription were lower than ratings with the DSL v5 Quiet prescription in both the sentences in quiet condition ($t(9) = 3.49$, $p = 0.007$, $d = 3.47$) and the sentences noise condition ($t(9) = 4.10$, $p = 0.003$, $d = 3.64$). These results indicated that the between-prescription differences measured in a previous study (Chapter 3) also were measured in the current study, independent of the DSP feature(s) used in combination with the base prescription.

4.7 Discussion

This study provided an evaluation of sentence recognition in noise and loudness perception with a group of children who wore hearing instruments fitted with several strategies for the management of non-quiet listening situations.

4.7.1 Sentence Recognition in Noise

Results of the sentence in noise recognition task showed significant benefit with the use of directional microphones. This result is consistent with existing literature, which has demonstrated the ability of directional microphones to improve children's ability to understand speech in the presence of competing noise (Gravel et al., 1999; Hawkins, 1984; Kuk et al., 1999; Ng et al., 2011). The improvement seen with directional microphone use was expected as directional advantage was likely maximized by the experimental set up which positioned the signal source at 0° and the noise source at 180° relative to the test position. The use of DNR did not have a significant effect on sentence recognition scores. This result is also in agreement with existing literature which has demonstrated no improvement in speech-in-noise performance with DNR in adults (Bentler & Chiou, 2006; Bentler et al., 2008; Dillon, 2001; Hu & Loizou, 2007; Nordrum et al., 2006; Ricketts & Hornsby, 2005) or with children (Pittman, 2011; Stelmachowicz et al., 2010). In the current study, the combination of directional microphones with DNR did not result in any significant difference in performance relative to use of directional microphones alone, which agrees with previous research (Nordrum et al., 2006; Peeters et al., 2009; Ricketts & Hornsby, 2005).

The individual data shown in Table 4-1indicate that nearly all participants improved their scores with directional microphones. While a small number of participants showed significant changes in score with DNR, the results are somewhat equivocal across those participants. Some participants obtained better scores and others obtained poorer scores with DNR.

The current study also evaluated the effects of combining DSP features with two different base prescriptions, specifically the DSL v5 Quiet and Noise prescriptions. Results of the sentence recognition in noise task demonstrated that scores improved with use of a directional microphone regardless of base prescription and that there was no interaction between base prescription and the use of DSP features. These group results suggest that no particular combination of DSP feature and base prescription led to decrements in sentence in noise recognition.

Table 4-1 also shows individual data for sentence recognition performance with the DSL v5 Noise prescription relative to performance with DSL v5 Quiet. The data are similar to the DNR data; individual performance with the DSL v5 Noise prescription alone was mixed. Some children had better performance while others showed poorer performance with DSL v5 Noise relative to DSL v5 Quiet. An examination of audiometric trends in relation to this result suggests that children with steeply sloping and profound hearing losses may perform more poorly with the DSL v5 Noise prescription. This result is not surprising given the reduction of gain and thus audibility in the low- and high-frequency regions. Children with steeply sloping losses likely rely more on their residual low-frequency hearing than their peers with flatter or milder losses.

Together, these results agree with the data presented in Chapter 3, which demonstrated no significant effect of prescription on sentence recognition performance between the DSL v5 Quiet and Noise prescriptions. Based on the group data alone, it would appear that any combination of DSP feature and base prescription evaluated in this study could be applied without detriment. However, a closer look at the individual data raises concerns because some children demonstrated poorer performance with the DSL v5 Noise prescription and DNR alone and in combination. Again, these concerns tended to arise for children with steeply sloping and profound hearing loss.

4.7.2 Loudness Perception

The main effect of prescription on loudness ratings was significant, indicating lower ratings with the DSL v5 Noise prescription than with the DSL v5 Quiet prescription. This result shows that lower loudness ratings can be achieved through application of a lower gain prescription. While this result is consistent with the data reported by Scollie et al. (2010b), which compared loudness ratings between DSL v4.1 and lower gain NAL-NL1 fittings, it is in contrast to the data presented in Chapter 3, which indicated no significant main effect of prescription on loudness ratings between DSL v5 Quiet and DSL v5 Noise fittings. A possible explanation for this discrepancy may be the reduction of variance associated with the use of repeated measures, which in turn increases statistical power (Portney & Watkins, 2000). The repeated measures analysis in this study subjected the prescriptions to more comparisons than in the previous study.

There was no significant main effect of DSP on loudness ratings over all levels of the loudness perception tasks. The use of directional microphones was not expected to result in a significant change in loudness ratings. Although hearing instrument frequency response was altered with directional microphone use, the change in output appeared to be level-dependent and relatively small with low-level inputs (Figure 4-2). DNR use was expected to demonstrate an effect based on the literature reporting improved listening comfort with DNR use (Bentler & Chiou, 2006; Bentler et al., 2008; Mueller et al., 2006; Ricketts & Hornsby, 2005). However, most research that has demonstrated improved comfort with use of DNR has used steady-state noise or noise with low modulation rates as the competing signal. The current study demonstrated no effect of DNR use. This lack of effect is likely due to the characteristics of the competing signal used in this study. Recall from Figure 4-4 that the DNR system of the hearing instruments in the current study demonstrated much more gain reduction with pink noise than with the Auditec four-talker babble (Auditec of St. Louis, 1971) used as the competing signal for the sentences in noise loudness perception task. This noise source was chosen in the interest of representing commonly encountered real-world listening situations (Fikret-Pasa, 1993). This choice is consistent with the goal of the current study, which was to identify a fitting strategy for use in the non-quiet environments experienced by children in their daily lives as described in Chapter 2.

The significant effect of loudness perception task condition was unexpected. As discussed in Chapter 3 and by Jacoby et al. (1988), it is possible that familiarization with the stimuli may have influenced loudness ratings in the sentences in noise condition. Experience with the sentence recognition task, which used similar stimuli, may have led to misinterpretation of the task resulting in ratings of intelligibility or SNR rather than (or along with) ratings of loudness perception. As such, loudness ratings in the sentences in noise condition were unintentionally biased towards lower ratings than in the sentences in quiet condition. For this reason, it may be inappropriate to derive clinical implications from comparisons of the loudness ratings between conditions of speech alone and speech in babble. Within each of these conditions, however, the relative changes caused by changes in hearing instrument gain or signal processing are likely valid for that type of listening situation.

Analysis of the "loud sounds" ratings indicated the ratings with the DSL v5 Noise prescription combined with a directional microphone were significantly lower than ratings with any other combination of prescription and DSP. This was likely due to the combined effects of the lower-gain DSL v5 Noise prescription and the low-frequency attenuation of the directional microphones at high input levels. Even though the combination of the DSL v5 Noise prescription with a directional microphone resulted in the lowest gain and thus output, it also resulted in best speech recognition in noise performance. Toward the combined non-quiet fitting goals of improving speech recognition in noise and reducing aversive ratings of loud sounds, the DSL v5 Noise prescription with a directional microphone is a potential strategy. However, further research into the effects of this strategy with children who have steeply sloping hearing loss may be warranted.

4.8 Conclusions

The current study addressed two research questions regarding fitting strategies for managing the non-quiet listening needs of children who wear hearing instruments. First, does the use of a prescribed frequency-gain response, directional microphone, DNR, or a combination result in better speech-in-noise recognition? There was significant improvement in sentence in noise recognition scores with use of a directional microphone, independent of the prescribed frequency-gain response. There was no significant difference between the prescriptions evaluated, specifically the DSL v5 Quiet and DSL v5 Noise prescriptions. Second, does the use of a prescribed frequency-gain response, directional microphones, DNR, or a combination result in differences in comfort ratings for loud sounds? The perceived loudness of loud sounds was rated lowest with the combination of the DSL v5 Noise prescription and a directional microphone. Overall, use of the DSL v5 Noise prescription with a directional microphone improved sentence in noise recognition performance and reduced loudness perception ratings for loud sounds relative to a typical clinical reference fitting with the DSL v5 Quiet prescription with no DSP features enabled. Therefore, the combination of the DSL v5 Noise prescription with a directional microphone may be a viable starting-point for further investigation into the management of children's non-quiet listening needs.

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Chapter 5

5 Discussion

The goals of this dissertation were to advance understanding of children's listening needs in non-quiet situations, to evaluate outcomes of existing hearing instrument fitting strategies to support these needs, and to begin to develop an evidence-based approach to support the breadth of non-quiet listening needs for children with hearing loss who wear hearing instruments.

Before summarizing the results of the studies in this dissertation, a brief discussion of the experimental design used for the evaluations of hearing instrument fitting strategies is presented below.

5.1 Overarching Design of Studies of Fitting Efficacy

The overall design of the studies presented in Chapters 3 and 4 are shown in Appendix A and Appendix B, respectively. The series of studies was designed with two practical factors taken into consideration. First, I wanted to be prepared for possible attrition because the participants were children and there were eight data collection sessions in addition to two practice sessions required. Second, frequency-gain response differences were expected to have the largest effect on speech audibility, so the comparison between the Desired Sensation Level (DSL) v5 Quiet and DSL v5 Noise prescriptions, independent of any advanced digital signal processing (DSP) features, was a necessary first step toward an optimal non-quiet listening strategy. Thus the design of the behavioural outcome measurement components was such that the effect of prescription alone could be quantified first, with a complete dataset obtained before beginning the evaluation of outcomes with the combination of DSP features and the two prescriptions evaluated. This design allowed for the independent comparison of the two prescriptions and the independent and combined comparisons of features paired with each of the prescriptions.

5.2 Summary of Results

The study presented in Chapter 2 demonstrated the diverse set of listening environments and situations, most of which are non-quiet, which children experience over the course of a school day. A child's day at school spans a broad range of sound and reverberation levels, which result in a range of listening needs across the day. Listening needs range from maximizing audibility when the environment and situation is relatively quiet and communication is the primary goal, to being able to understand speech when there is competing noise present, and to improving comfort when the environment or situation is loud. Due to the presence of competing noise most of the time, children are often listening to speech produced with a raised vocal effort as shown in the spectral data in Chapter 2.

The study presented in Chapter 3 demonstrated the effects of the alternate frequency-gain response of the DSL v5 Noise prescription on consonant recognition in quiet, sentence recognition in noise, and loudness perception. Results indicated that the DSL v5 Noise prescription generally maintained consonant recognition performance; however, consonant recognition was approximately 4% poorer with low-level (50 dB SPL) input relative to the DSL v5 Quiet prescription. The DSL v5 Noise prescription had no significant effect on sentence recognition in noise performance. Loud sounds were rated as being more comfortable with the DSL v5 Noise prescription than with the DSL v5 Quiet prescription.

The study presented in Chapter 4 demonstrated the effects of DSP features when combined with prescribed frequency-gain responses on sentence recognition in noise and loudness perception. Results indicated that use of a directional microphone significantly improved children's sentence recognition in noise performance regardless of the base prescription; the use of digital noise reduction (DNR) had no effect on performance. Loudness perception results indicated that combining a directional microphone with the DSL v5 Noise prescription resulted in more comfortable ratings for loud sounds than with any other combination of base prescription and DSP.

Two conditions were used for evaluating loudness perception; sentences presented in quiet and sentences presented in competing noise. Interestingly, there was an unexpected effect of the loudness perception condition, which indicated that children rated sentences in competing noise lower in loudness than sentences presented in quiet. This unanticipated effect of condition was discussed in Chapter 3, where the potential confounding effects of memory as suggested by Jacoby et al. (1988) and the possible misinterpretation of the task as one of rating intelligibility were described.

5.3 Overall Contribution to the Literature

The results presented in this body of work generally agree with the existing literature and also serve to expand on our current knowledge through use of novel approaches to investigating the non-quiet listening needs of children with hearing loss.

Existing literature has indirectly demonstrated the diversity of listening environments and situations experienced by children. Pearsons, Bennet, and Fidell (1977) reported that there was a broad range of speech and noise levels across a variety of common listening environments. Scollie et al. (2010) stated that children reported a broad range of listening situations and that they preferred different frequency-gain responses depending on the listening situation. Gatehouse et al. (1999; 2003, 2006a, 2006b) demonstrated that benefit from hearing instrument processing strategies was correlated with the degree of diversity in an individual's auditory ecology. Studies of classroom acoustics and listening have demonstrated that use of frequency modulation (FM) systems optimizes listening in the traditional educational classroom environment where the teacher is the primary talker (Boothroyd & Iglehart, 1998; Hawkins, 1984; Lewis, Feigin, Karasek, & Stelmachowicz, 1991; Lewis, Crandell, Valente, & Horn, 2004; Pittman, Lewis, Hoover, & Stelmachowicz, 1999). Together, these existing studies suggest the importance of considering the listening needs of children beyond the clinic, where hearing instrument fitting and evaluation typically occur, and beyond listening in the tradition instructional classroom setting, where children are undisputedly well served by FM systems.

The current body of work sought to directly evaluate the listening environments, situations, and needs experienced by children at school, outside traditional classroom instruction. To this end, cohorts of children and their environments were observed and measured directly rather than through self-report measures as has been done in previous studies (Gatehouse et al., 1999; Gatehouse et al., 2003, 2006a, 2006b; Scollie et al., 2010). Further, this body of work sought to address children's performance with available hearing instrument fitting strategies and their combinations, including an evaluation of the DSL v5 Noise prescription.

5.4 Implications for Pediatric Hearing Instrument Fitting

This is the first study evaluating the DSL v5 Noise prescription and the first study addressing the combination of different generic prescriptions with commonly used noise management features. The combination of this evaluation of prescriptions and noise management features with the identified listening needs described in Chapter 2 offers a starting point for the understanding and management of the non-quiet and non-instructional listening needs of children.

Currently, practice guidelines regarding non-quiet listening management are mixed across various audiology organizations. Most recommend a single listening program for children (AAA, 2003; Bagatto, Scollie, Hyde, & Seewald, 2010; CASLPO, 2002; Foley, Cameron, & Hostler, 2009); however, this recommendation does not meet the identified needs and preferences of children for listening across the varied environments and situations they experience (Scollie et al., 2010). Recommendations regarding the use of DSP features for children is also mixed; some organizations recommend against using directional microphones and DNR (AAA, 2003; Foley et al., 2009), others consider these features to be viable options (Bagatto et al., 2010; CASLPO, 2002), and others recommend the use of directional microphones and automatic switching algorithms universally (King, 2010). The current body of work has confirmed and described the diversity of non-quiet listening environments and situations that children experience in a typical day at school and has thus demonstrated the need for appropriate hearing instrument fitting strategies to manage non-quiet listening. Further, this body of work has also demonstrated the potential efficacy of using a prescribed frequency-gain response combined with a directional microphone with regard to improving sentence recognition in noise and improving comfort for loud sounds.

Clinicians attempting to address the non-quiet listening needs of their pediatric clients may have concerns about losing valuable speech audibility, because all of the available tools reduce audibility for some signals, including speech and non-speech. In this research, DSL v5 Noise combined with a directional microphone showed the most promise as a non-quiet listening solution for children. This combination is also attractive as a non-quiet solution because the effects of a prescribed frequency-gain response and a directional microphone are independent of signal characteristics (i.e., modulation depth and frequency). However, clinicians may be concerned about non-frontal listening, which can be negatively impacted by a directional microphone (Ricketts et al., 2007). Thus, a safe compromise, until dependable automatic or manual program switching is confirmed, may be to use the DSL v5 Noise prescription alone as a non-quiet listening solution because it provides improved comfort for loud sounds without detriment to speech recognition at average levels and above.

Individual clinical outcome measurement may be warranted as indicated by individual data trends. Group results indicated no difference in sentence recognition in noise performance with DSL v5 Noise, however three children had better performance and three children had poorer performance with DSL v5 Noise than with DSL v5 Quiet. A possible explanation for these differences may be the child’s degree and configuration of hearing loss. The individual data indicated that poorer performance with DSL v5 Noise occurred for children with steeply sloping losses. Therefore, any potential non-quiet listening strategy should be evaluated on an individual basis. Ching et al. (2010) recommended individual evaluation of amplification needs and outcomes to meet the diverse needs of children. Similarly, Ricketts and Galster (2008) suggest the importance of considering individual differences in children’s ability to accurately orient to a talker and thus benefit from directional microphones.

Finally, the data presented in Chapter 2 indicated that children spend the majority of their days in non-quiet listening environments and situations. The data also indicated that children are often listening to speech produced with a raised vocal effort as talkers raise their voices to be heard above the almost constant presence of competing signals. These results suggest the importance of considering the effects of vocal effort on the spectral shape of speech inputs in the generation of prescriptive targets, as is done by the DSL v5 algorithm (Scollie et al., 2005).

5.5 Strengths and Limitations

5.5.1 Strengths

A strength of this body of work is its real-world representativeness. This was enabled through novel design choices toward the goal of assessing real-world applicability of various combinations of non-quiet listening strategies. For example, a novel approach was demonstrated in the testing of children on behavioural outcome measures in their actual school setting (Figure 5-1). This approach allows for inferences on real-world effectiveness, which is more appropriate to the goals of this body of work than study designs that are limited to assessing experimental efficacy in highly controlled environments.

> *Efficacy (can it work?) is the extent to which an intervention does more good than harm. The testing is conducted under ideal circumstances (e.g., fixed directional microphone in a sound booth with fixed noise sources at the nulls with the child positioned ideally). Effectiveness (does it work in the real world?) assesses whether an intervention does more good than harm when used in typical practice (e.g., fixed directional microphone compared to an omnidirectional response in real-world listening conditions with the child interacting in the environment naturally).*
> *(Palmer, 2007, p. 121)*

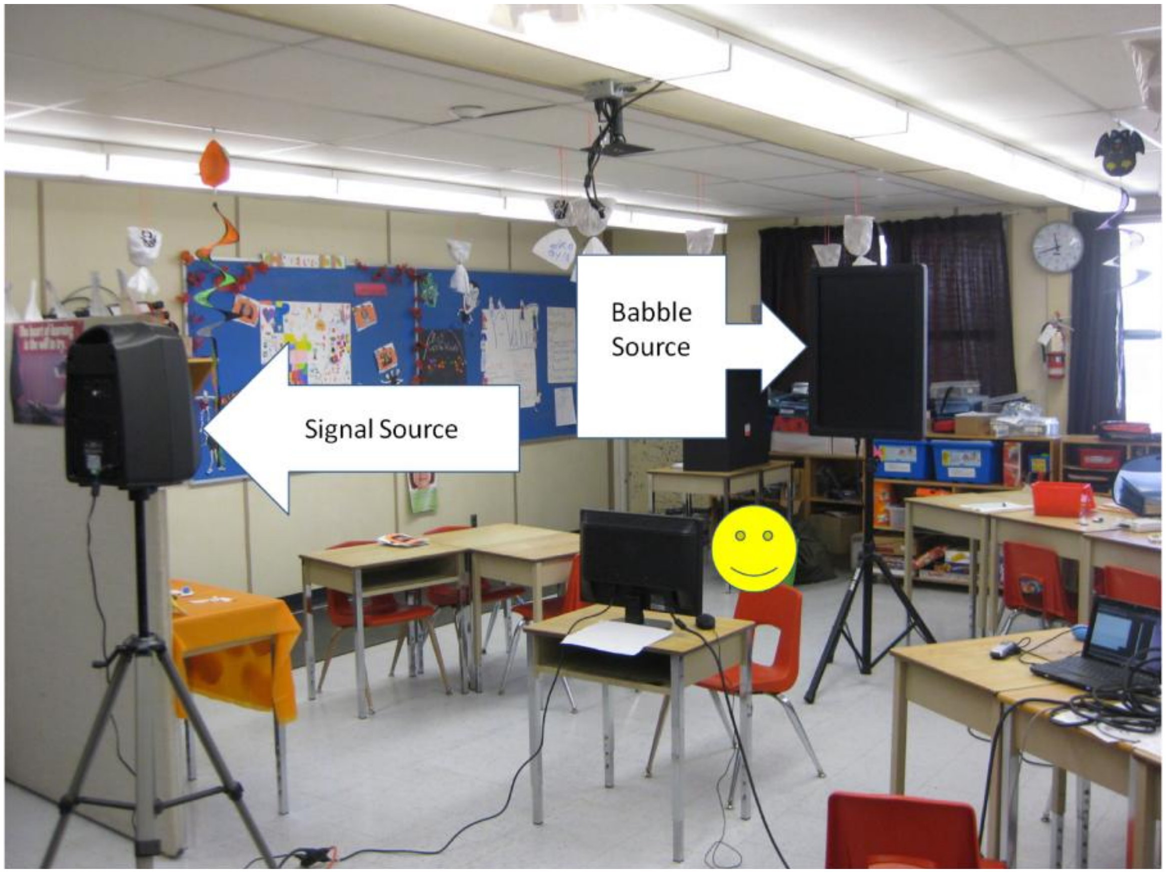

Figure 5-1: Photograph of the test setup at the elementary school.

The babble used in this study as the competing signal across all measures was carefully chosen to best approximate a common real-world listening challenge. This choice may have impacted results, and may be the explanation for the lesser benefit seen from DNR in Chapter 4, compared to previous studies. The DNR feature of the hearing instruments did not impose much gain reduction in response to the Auditec four-talker babble (Auditec of St. Louis, 1971) used as the competing signal. This is considered a strength because the Auditec four-talker babble was chosen specifically to challenge the DNR function in a situation representative of real-world listening.

5.5.2 Limitations

A limitation of this body of work was that it was not a full effectiveness evaluation because it did not include a real-world trial. In addition, although the listening environments and situations of the children in the study were examined in detail, only a small number of children were included. This restriction limits the generalizability of the results. As mentioned above, even if a generalizable solution was found with a larger sample size, pediatric audiology will likely always require an individualized approach and possibly individual outcome measurement. Additionally, speech recognition has been shown to be dependent on age and hearing loss (Boothroyd, 1997; Elliott, 1979; Fallon, Trehub, & Schneider, 2000; Fallon, Trehub, & Schneider, 2002; Scollie, 2008; Stelmachowicz, Hoover, Lewis, Kortekaas, & Pittman, 2000) and the studies presented in Chapters 3 and 4 included a small number of children and lacked a continuous span across the age range. This study was only single-blind, with the researcher aware of the condition being tested due to practical limitations. Given that the researcher scored the BKB-SIN task, this awareness could be considered a limitation.

A further limitation of this work relates to experimental control versus generalizability. The studies presented included two groups of participants who were tested at two different sites in order to be representative of their school environment and to facilitate study participation. This difference prevented analysis of age-related trends or comparison of the two groups' performance with one another, as the rooms differed considerably. For this reason, between-group analysis was not performed but could be examined further in future studies.

5.6 Future work

The series of studies comprising this body of work contribute to the existing literature and also raise questions for further study. Larger scale investigation and description of the auditory environments, situations, and ecology of children would be useful in order to develop a broader (beyond schools into homes and community activities) and more generalized understanding of children's listening needs. Although this preliminary work has identified some promising solutions for managing non-quiet listening, the practical application of these solutions needs to be investigated from an effectiveness perspective. As discussed above, a non-quiet listening strategy would be best employed as a second listening program within a hearing instrument. In order to make use of such a program, the hearing instrument would need to be manually switched by the child or at the discretion of an automatic switching algorithm. Although there are some data regarding the appropriateness and efficacy of these switching methods (Ricketts, Picou, Galster, Federman, & Sladen, 2010), results may differ by age or individual and this is something that should be evaluated further. This could be facilitated by the data logging available in hearing instruments coupled with further observation, self-report data, and interviews with children to assess how their non-quiet listening needs are being managed and addressed by the addition of a second listening program. With a better understanding of how to best make use of a non-quiet listening strategy, pediatric fitting protocols could be developed or expanded to include non-quiet listening management.

Concerns regarding the negative impacts of directional microphones on non-frontal listening could be addressed through continued evaluation of children's performance with manual and automatic switching combined with speech recognition and awareness evaluation of speech sources from non-frontal locations.

In summary, toward the development of a pediatric non-quiet listening protocol, the following additional research questions are proposed:

i) What are children's non-quiet listening needs beyond the school setting (i.e., at home, in the community)?

An observational study employing dosimetry measures as in Chapter 2 could be extended to shadow children's experiences in vehicles, at home, after-school, and on weekends (participating in community activities). Improved understanding of the listening landscape of children outside of schools altogether could be useful because language learning also occurs through overhearing (Moeller, Tomblin, Yoshinaga-Itano, Connor, & Jerger, 2007). Given that many of these instances of overhearing occur independent of quiet, face-to-face conversation, knowledge of the acoustic and practical challenges of these instances would be informative for the development of non-quiet listening strategies. As shown in this body of work and previous literature, these non-quiet strategies also need to consider non-frontal sound sources to include overhearing as a source of important auditory input (Ricketts et al., 2007).

ii) If children cannot reliably switch between programs (Ricketts et al., 2010) but desire a second program (Scollie et al., 2010), can we improve automatic switching algorithms?

Preliminary data suggests that hearing instrument classifications disagree with a trained adult listener with normal hearing (Crukley & Scollie, 2010). One potential model to improve automatic switching algorithms could be to pair a trained listener with a Master Hearing Aid (MHA; Grimm, Herzke, Berg, & Hohmann, 2006), to train an algorithm in real-time, correcting its "judgments" of sound types outside the constraints of the processing power of hearing instruments. Additional related research should evaluate the electroacoustic properties of non-quiet listening strategies. Electroacoustic evaluation should include sensitivity of DSP algorithms to real-world representative noise signals like Auditec four-talker babble. Measurements could be conducted to determine if a given proprietary DNR or automatic switching algorithm is activated by the noise signal.

iii) How can the DSL v5 Noise prescription be modified to accommodate individuals with steeply sloping hearing losses, who rely on residual low-frequency hearing?

Given the trend that children with steeply sloping losses tended to perform more poorly with the prescribed frequency-gain response of the DSL v5 Noise prescription, the above question is necessary to improve the prescription's accommodation of the range of children's hearing loss configurations. One hypothesized approach to accommodate steeply sloping hearing losses could be to limit the amount of low-frequency gain reduction such that low-frequency output targets do not fall below the level of unamplified speech. A large-scale efficacy study could be undertaken to improve understanding of patterns of optimal frequency-gain settings for various degrees and configurations of hearing loss. This type of data could then inform the refinement of future versions of the DSL Noise prescription.

For the purposes of future studies of pediatric non-quiet hearing instrument fitting, the following fitting outcome measurement protocol can be deduced from this series of studies:

i) Individual aided loudness perception measurement, with a focus on high-level inputs.

This would allow for identification of children for whom aversive loudness with the DSL v5 Quiet prescription is a problem, which can then be addressed through use of a lower gain prescription for non-quiet listening.

ii) Sentence recognition in noise testing with a prescribed non-quiet frequency-gain response.

This would allow for identification of children for whom a lower gain prescription such as DSL v5 Noise results in poorer sentence recognition in noise.

iii) Individual candidacy assessment and counseling regarding the use of a second program.

This would allow for identification of children who may or may not be able to make use of a manually selected non-quiet listening program.

5.7 Concluding Statements

The research questions addressed in this overall program of research were:

Study 1

i) What are the reverberation times across settings within the school or daycare?
ii) What is the spectral shape of signals that children experience?
iii) What are typical noise and sound levels and sources in various school settings throughout a school day?

Study 2

i) Does use of the two prescriptions result in differences in consonant recognition?
ii) Does use of the two prescriptions result in a difference in sentence recognition in noise performance?
iii) Does use of the two prescriptions result in different comfort ratings for loud sounds?

Study 3

i) Does the use of a prescribed frequency-gain response, directional microphone, DNR, or a combination result in better speech-in-noise recognition?
ii) Does the use of a prescribed frequency-gain response, directional microphones, DNR, or a combination result in differences in comfort ratings for loud sounds?

The combined results of the series of studies emphasize the need for continued research into non-instructional and non-quiet listening situations for children. School days are currently dynamic, with technological and pedagogical advances resulting in a range of activities, only some of which involve the teacher speaking at the front of room (Gibson, 2001). The study presented in Chapter 2 demonstrated the auditory diversity that this educational shift presents.

This research offers greater understanding of children's listening needs, the first evaluation of the DSL v5 Noise prescription, the first study evaluating the combined effects of prescription with hearing instrument features, and a novel research design bringing us closer to children's real-life listening needs.

The results presented in this body of work have demonstrated the broad range of listening environments and situations that children encounter over the course of a school day, many of which are non-quiet and non-instructional. Current practice guidelines do not offer recommendations for managing the listening needs of children across these encountered environments and situations and the guidelines for pediatric hearing instrument fitting does not offer much flexibility beyond listening in quiet or listening to a teacher during didactic learning. For these reasons, novel or redesigned pediatric hearing instrument guidelines should be developed that include consideration for listening in the non-quiet and non-didactic environments and situations that are part of children's daily lives. This body of work also serves to fill the gaps in knowledge regarding the combination of alternate prescriptions/frequency-gain responses with the DSP features available in hearing instruments. The results have shown that DSL v5 Noise combined with a directional microphone could be a viable starting place for managing children's non-quiet listening needs.

5.8 References

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Appendix A: Design of Chapter 3

Study 3: Comparison of Prescriptions

	Independent Variable: Prescription (A)	
Dependent Variable	A1	A2
Consonant Recognition (DFD) at 50 dB SPL		
Consonant Recognition (DFD) at 70 dB SPL		
Sentence Recognition in Noise (BKB-SIN)	DSL Quiet	DSL Noise
Loudness Perception Sentences in Quiet		
Loudness Perception Sentences in Noise		

Appendix B: Design of Chapter 4

Study 4: Effects of Features

	Independent Variables: Prescription (A) + DSP Feature (B)							
Dependent Variable	A1B1	A1B2	A1B3	A1B4	A2B1	A2B2	A2B3	A2B4
Sentence Recognition in Noise (BKB-SIN)	DSL Quiet	DSL Quiet + DIR	DSL Quiet + DNR	DSL Quiet + DIR + DNR	DSL Noise	DSL Noise + DIR	DSL Noise + DNR	DSL Noise + DIR + DNR
Loudness Perception Sentences in Quiet	DSL Quiet	DSL Quiet + DIR	DSL Quiet + DNR	DSL Quiet + DIR + DNR	DSL Noise	DSL Noise + DIR	DSL Noise + DNR	DSL Noise + DIR + DNR
Loudness Perception Sentences in Noise	DSL Quiet	DSL Quiet + DIR	DSL Quiet + DNR	DSL Quiet + DIR + DNR	DSL Noise	DSL Noise + DIR	DSL Noise + DNR	DSL Noise + DIR + DNR

Note. Abbreviations for this table are as follows: digital signal processing (DSP), directional microphone (DIR), and digital noise reduction (DNR).

Appendix C: Ethics Approval Notices

Western

Office of Research Ethics

The University of Western Ontario
Room 4180 Support Services Building, London, ON, Canada N6A 5C1
Telephone: (519) 661-3036 Fax: (519) 850-2466 Email: ethics@uwo.ca
Website: www.uwo.ca/research/ethics

Use of Human Subjects - Ethics Approval Notice

Principal Investigator: Dr. S. Scollie
Review Number: 17030E **Review Level:** Expedited
Review Date: April 07, 2010 **Approved Local # of Participants:** 20
Protocol Title: Pediatric Hearing Aid Prescription for Non-Quiet Environments
Department and Institution: Health & Rehabilitation Sciences, University of Western Ontario
Sponsor:
Ethics Approval Date: April 30, 2010 **Expiry Date:** June 30, 2011
Documents Reviewed and Approved: UWO Protocol, Letter of Information and Consent and Assent Letter (Fairmont Public School), Letter of Information and Consent and Assent Letter (Montcalm Secondary School), Letter of Information and Consent and Assent Letter (Child Amplification Lab), Authorization for Release of Information.

Documents Received for Information:

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced study on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the UWO Updated Approval Request Form.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the HSREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of monitor, telephone number). Expedited review of minor change(s) in ongoing studies will be considered. Subjects must receive a copy of the signed information/consent documentation.

Investigators must promptly also report to the HSREB:

a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) all adverse and unexpected experiences or events that are both serious and unexpected;
c) new information that may adversely affect the safety of the subjects or the conduct of the study.

If these changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the newly revised information/consent documentation, and/or advertisement, must be submitted to this office for approval.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

Chair of HSREB: Dr. Joseph Gilbert
FDA Ref. #: IRB 00000940

Ethics Officer to Contact for Further Information			
☐ Janice Sutherland (jsutherl@uwo.ca)	☐ Elizabeth Wambolt (ewambolt@uwo.ca)	☒ Grace Kelly (grace.kelly@uwo.ca)	☐ Denise Grafton (dgrafton@uwo.ca)

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UWO HSREB Ethics Approval - Initial
V.2008-07-01 (rptApprovalNoticeHSREB_Initial) 17030E Page 1 of 1

Western

Office of Research Ethics

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Use of Human Subjects - Ethics Approval Notice

Principal Investigator: Dr. S. Scollie
Review Level: Expedited
Review Number: 17030E
Revision Number: 1
Review Date: November 25, 2010
Approved Local # of Participants: 20
Protocol Title: Pediatric Hearing Aid Prescription for Non-Quiet Environments
Department and Institution: Health & Rehabilitation Sciences, University of Western Ontario
Sponsor:
Ethics Approval Date: November 25, 2010
Expiry Date: June 30, 2011
Documents Reviewed and Approved: Revised administrative changes and letter of information and consent. Andrea Dunn has been added to this study team.
Documents Received for Information:

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

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Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

Chair of HSREB: Dr. Joseph Gilbert
FDA Ref. #: IRB 00000940

Ethics Officer to Contact for Further Information			
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This is an official document. Please retain the original in your files.

cc: ORE File

Curriculum Vitae

Name:	Jeffery Crukley
Post-secondary Education and Degrees:	McMaster University London, Ontario, Canada 1996-2000 B.Sc. (Hons)
	The University of Western Ontario London, Ontario, Canada 2004-2007 M.Sc. Communication Sciences and Disorders, Audiology
	The University of Western Ontario London, Ontario, Canada 2007-2011 Ph.D. Health and Rehabilitation Sciences, Hearing Science
Significant Honours and Awards:	Natural Sciences and Engineering Research Council Post-graduate Scholarship Doctoral 2008-2011
	International Hearing Aid Research Conference Student Scholarship 2008
	A. Charles Holland Scholarship for two-month research internship at Vanderbilt University 2008
	Canadian Academy of Audiology Outstanding Poster Presentation 2007
	Natural Sciences and Engineering Research Council Post-graduate Scholarship Masters 2006-2007
	Ontario Graduate Scholarship 2007-2008, Declined 2006-2007, Declined 2008-2009
	Natural Sciences and Engineering Research Council Student Research Award 2005

Related Work Experience:	Part-time Faculty (Lecturer) The University of Western Ontario 2008-Present
	Teaching Assistant The University of Western Ontario 2005-2010

Selected Publications:

Articles in Peer-Reviewed Journals

Crukley, J., Scollie, S., Parsa, V. (In review). An exploration of school-age listening landscapes. *Journal of Educational Audiology.*

Scollie, S., Bagatto, M., Moodie, S., Crukley, J. (Accepted). Accuracy and reliability of an RECD procedure implemented within a hearing aids. *Journal of the American Academy of Audiology*.

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Walsh, K.A., Crukley, J., Megyesi, J., Wilson, J.X., Gelb, A.W., Hammond, R. (2001). Antioxidant protection from HIV-1 gp120 induced neuroglial toxicity. *37th Meeting of The Canadian Congress of Neurological Sciences.* In *The Canadian Journal of Neurological Sciences*, *29* Supp 1.

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Peer-reviewed Poster Presentations

Crukley, J., Scollie, S. (2010). A school-age listening landscape: Implications for hearing aids. *International Hearing Aid Research Conference* in Lake Tahoe, CA.

Crukley, J., Scollie, S., Cheesman, M., Parsa, V., Beaulac, S. (2008). Sound localization abilities of listeners with normal hearing and adults with hearing impairment. *International Hearing Aid Research Conference* in Lake Tahoe, CA.

Crukley, J., Scollie, S., Cheesman, M., Parsa, V., Beaulac, S. (2007). The effects of age and background noise on human sound localization. *4th International Pediatric Conference - A Sound Foundation Through Early Amplification.*

Crukley, J., Scollie, S., Cheesman, M., Parsa, V., Beaulac, S. (2007). Sound localization abilities of children versus adult listeners. *10th Annual Conference of The Canadian Academy of Audiology.*