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Recognition and Comprehension of Speech in Noise in School-Aged Children with Unilateral Hearing Loss

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RECOGNITION AND COMPREHENSION OF SPEECH IN NOISE IN SCHOOL-AGED CHILDREN WITH UNILATERAL HEARING LOSS

A Dissertation Presented

by

AMANDA M. GRIFFIN

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
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Communication Disorders

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DEDICATION

To my husband.
For his endless love, support, and patience.

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I wish to thank my committee members for their unceasing support. I would like to thank Sarah Poissant most especially for her unwavering confidence in me. I would like to thank Richard Freyman for supporting my graduate school journey both intellectually and financially. Without his continued support, this project would not have been possible. I would also like to thank Craig Wells for agreeing to serve on my thesis committee; your statistical guidance was invaluable.

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I would finally like to extend my deepest gratitude to all the children and families who graciously participated in this research project.

ABSTRACT

RECOGNITION AND COMPREHENSION OF SPEECH IN NOISE IN SCHOOL-AGED CHILDREN WITH UNILATERAL HEARING LOSS

MAY 2015

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Sentence recognition and auditory comprehension abilities of young adults with normal hearing (NH) and school-age children with NH and unilateral hearing loss (UHL) were tested in a mixed design. In Experiment 1, subjects' sentence recognition abilities were measured in the presence of speech spectrum noise (SSN) and two-talker child babble (TTB) in co-located and spatially-separated target and masker configurations. In all conditions, reception thresholds for sentences (RTS) improved with age from six-to 12 years. Speech spectrum noise proved to be a more effective masker than TTB in all listening conditions, suggesting subjects were able to take advantage of temporal and spectral fluctuations in the masker. By 12 years of age, RTS appeared to be adult-like when children listened in the presence of SSN, but were still immature in TTB. Across all listening conditions, a majority of UHL subjects' RTS fell outside ±1 standard deviation of the NH mean, indicating poorer performance for this group of listeners. Performance of UHL subjects heavily depended on spatial configuration and was poorest when the masker was directed towards their normal-hearing ear. In Experiment 2, subjects' auditory comprehension abilities were measured in the presence of TTB at a variety of signal-to-noise ratios (SNRs). When averaged across age, NH subjects performed similarly across the different listening conditions. For most UHL subjects, performance was similar to NH subjects in all comprehension tasks suggesting like NH subjects they made use of story context to support understanding even when audibility was compromised and likely took advantage of gaps in the TTB and spatial separation of the target and masker to better glimpse/hear the target. The findings of the current study improve our understanding of both simple and complex auditory abilities of school-aged children with NH and UHL in classroom-like, noisy environments. Furthermore measurable auditory deficits were detected in the study's sample of children with UHL.

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INTRODUCTION

1.1 A Preview

Before the advent of universal newborn hearing screening, children born with hearing loss were often not identified and diagnosed until two and one-half to three years of age. Children with milder degrees of hearing loss were often diagnosed even later, typically upon entering school. Today, approximately 95% of newborns in the US are screened for hearing loss at birth, which has dramatically decreased the average age of identification to two-to-three months of age (White, 2003; Harrison, et al., 2003; Mitchell & Karchmer, 2004; White, 2008; Hoffman and Beauchine, 2007).

Research has clearly shown that more positive outcomes occur for children born with hearing loss who are identified early and receive early intervention services. Hearing is essential to the development of speech and language, literacy, and learning. Early identification and intervention can lessen the impact of hearing loss on a child's development (Sininger, et al., 2010; Yoshinaga-Itano, et al., 2010). A recent study compared the speech and language outcomes of children with hearing loss who were early- versus late-identified. The vast majority of children who were identified early and received aggressive aural habilitative services demonstrated age-appropriate speech and language skills by just three years of age (Fulcher, et al., 2012), something that would have been unimaginable a few decades ago.

Despite the expansion of newborn hearing screening programs and quality early intervention services, there are some children with hearing loss who are missed by the screening process or who remain underserved. The most obvious group of children is that with late-onset or progressive hearing losses. Perhaps a less obvious group is that with “minimal” forms of hearing loss, defined as mild degrees of bilateral hearing loss or unilateral hearing loss (UHL). Not all newborn hearing screening programs routinely identify children with mild, bilateral hearing loss; these children can pass their newborn hearing screening despite the presence of hearing loss (i.e., false negative). This is largely due to sensitivity differences among screening measures (Stein, 1999). For example, assessment via otoacoustic emissions will usually result in a pass for infants with mild hearing losses as opposed to assessment via auditory brainstem response testing which will most often result in a referral for audiological testing for those same infants. While children with moderate-to-profound degrees of UHL will be detected at birth through either newborn hearing screening measure, they frequently receive delayed intervention services.

Suspending or delaying intervention to children with UHL was at one point in time the standard of care and in many parts of the country this philosophy remains. Historically, clinicians and researchers believed that children with UHL would develop typically since they had one normal-hearing ear. However, in the mid-to-late 1980s researchers began to uncover significant academic issues in this population. Since then, a body of knowledge has emerged suggesting that children with UHL are at significant risk for speech and language delays, academic underachievement, and behavioral issues (Peckham and Sheridan, 1976; Bess and Tharpe, 1984, 1986; Culbertson and Gilbert, 1986; Oyler, et al., 1988; Bovo, et al., 1988; Jensen, et al., 1989; Young, et al., 1997; Watier-Launey, et al. 1998; Kiese-Himmel, 2002; Sedey, et al., 2002; Borg, et al., 2002; Most, 2004; Lieu, et al., 2010). Despite this increased knowledge, widespread clinical practice has not changed. Many clinicians feel that there are a lack of data directly tying difficulties experienced by some children with UHL to auditory disorders. In reality, we have a limited understanding of the auditory abilities of children with UHL. There is little knowledge of how they function auditorily in realistic listening environments. Children with UHL are arguably underserved clinically and also understudied. In order to better serve this population, it is imperative to first better define the challenges associated with UHL. In order to understand the relative difficulties of children with UHL it is necessary to also characterize normal auditory development over the age range of interest. The objective of the current research project was to further our understanding of how children with UHL and children with normal hearing (NH) hear and comprehend speech in listening situations typical of a classroom environment.

1.2 Population

Hearing loss is the most prevalent developmental abnormality present at birth (White, 1997), more common than other well-known congenital disorders including Down Syndrome, cleft lip or palate, limb defects, spina bifida, and sickle cell anemia. In 2010, the Center for Disease Control's Early Hearing Detection and

Intervention Program reported an incidence of permanent hearing loss in newborns in the United States at 4,923. Of the 4,923 diagnosed permanent hearing losses, 1,768 (36%) of them were unilateral. Most of those losses were deemed sensorineural in nature (n=816), followed by conductive (n=546), unknown (n=194), mixed (n=120), and auditory neuropathy (n=94). The incidence of UHL for all live births is approximately 0.83-1.7/1,000 (Vartiainen and Karjalainen, 1998). This increases considerably to approximately 3.4% when more vulnerable populations are isolated, such as well-babies with hearing loss risk factors and neonatal intensive care unit (NICU) graduates (Cone-Wesson, et al., 2000). The school-age population with UHL has previously been estimated at 2-3/1,000 (Bess, et al., 1998) and if mild unilateral losses are included, some estimates rise to 13/1,000. The number of school-aged children (five-19 years) in the US was projected to be 62,379,999 in 2013 (U.S. Census Bureau Population Division, 2014). If it is assumed 13/1000 of those children have unilateral hearing loss, it can estimated that at least 800,000 school-aged children in the US had UHL in 2013. With approximately one-third of all hearing losses being unilateral in configuration, there is clearly a significant number of patients in need of evidenced-based practices.

1.3 Current Management

The average age of identification of hearing loss has dropped from two and one-half-to-three years to two-to-three months of age since the widespread adoption of newborn hearing screening in the 1990s (Harrison et al., 2003; Hoffman

& Beauchine, 2007; White, 2008). However, despite early-identification of hearing loss, children with UHL often experience a delay of intervention services by seven to 30 months after diagnosis and are generally fit with amplification later than children with bilateral hearing loss (Vohr, 1995; Dalzell, et al., 2000; Fitzpatrick, et al., 2010). Failing to provide auditory input to an “aidable” ear risks the known consequences associated with auditory deprivation: neural reorganization (Scheffler, et al., 1998; Schmithorst, et al., 2005; Propst, et al., 2010; Tibbets, et al., 2011), declines in word-recognition (Silverman, et al., 2006), and poor device compliance (Kiese-Himmel, 2002; Yoshinaga-Itano, et al., 2008). Rates of amplification use in children with UHL are 7-48% (Yoshinaga-Itano, et al., 2008; Fitzpatrick, et al., 2010). Typical amplification and assistive listening devices recommended for children with UHL include a traditional hearing aid, contralateral routing of signal (CROS) hearing aid, osseointegrated implantable hearing device (e.g., Baha), and frequency-modulation (FM) systems. A cochlear implant (CI) is presently being trialed in Europe and at select medical centers in the US for patients with single-sided deafness (NH in one ear and severe-profound HL in the other ear) (Hassepass, et al., 2013; Plontke, et al., 2013).

Current recommendations regarding the audiological management of UHL in children depend on the child’s needs, the family’s motivations and the clinician’s judgment. According to the American Academy of Audiology Pediatric Amplification Protocol (2003), “The decision to fit a child with UHL should be made on an individual basis, taking into consideration the child’s or family’s preferences as well as audiologic, developmental, communication and educational factors.” For pediatric patients, a “wait to fail” model is often followed – amplification or assistive listening devices are not recommended until the child presents with developmental delays or educational challenges. This is a less than ideal approach given there is a known sensitive period for auditory development. When the auditory system is deprived of early stimulation, cortical reorganization occurs. Areas in the brain once dedicated to receiving auditory input are reassigned to other functions (e.g., for the visual system) – a near permanent change in the neural network (Bavelier and Neville, 2002). A traditional hearing aid fitted early in life and worn regularly has the potential to prevent neural reorganization (in part) and restore some level of binaural hearing cues for certain patients, which may lead to improvements in sound localization and speech understanding abilities. However if these devices are fitted after the sensitive period for auditory development has passed, the likelihood of patients receiving full benefit from them is slim. Today, clinicians lack quality evidence needed to recommend one treatment method over another for UHL and currently make their decisions on a case-by-case basis, relying mostly on their clinical judgment. This ultimately leads to a wide variety of treatment options being implemented, ensuring a myriad of outcomes for children with UHL.

1.4 Psychoeducational Outcomes

Historically, audiologists, physicians, and educators assumed that children with unilateral sensorineural hearing loss would experience few, if any, educational or communicative difficulties related to their hearing loss. In their seminal textbook on hearing in children Northern and Downs (1984) wrote “…audiologists and otolaryngologists are not usually concerned over such deafness other than to identify its etiology and assure the parents that there will be no handicap (p. 143)." Clinicians were not overly concerned since these patients had one NH ear, which was thought to be sufficient for typical development. However, in the mid-to-late 1980s researchers began to collect data on the impact of UHL on a child's development. The initial results were much of a shock to the audiological community. Serious academic and behavioral issues were exposed in a subset of children with UHL. In one comprehensive study conducted by Bess and colleagues (1986), 35% of subjects with UHL were found to have failed at least one grade, making them 10 times more likely for grade retention than their peers with NH. Other researchers later corroborated this finding, discovering grade retention rates ranging from 18-40% in children with UHL (Bess and Tharpe, 1984, 1986; Oyler, et al., 1988; Bovo, et al., 1988; Jensen, et al., 1989; Watier-Launey, 1998).

Aside from the sobering grade retention rates, researchers additionally found that children with UHL were simply less likely to be performing at grade level when compared to their NH peers (Bess and Tharpe, 1984, 1986; Oyler, et al., 1988; English and Church, 1999). When compared to district norms, children with UHL have shown specific academic difficulties in reading comprehension, vocabulary, and language (Blair, et al., 1985). Given their academic difficulties, children with UHL, not surprisingly, have an increased need for special support services. It is estimated that 12-41% of children with UHL receive special education services (Bess and Tharpe, 1986; Bovo, et al., 1988; Oyler, et al., 1988; Jensen, 1989; English et al., 1999; Blamey, et al., 2001; Yoshinaga-Itano, et al., 2008; Lieu, et al., 2010;

2012). Interestingly, it has been found that of the children with UHL *not* receiving special educational services, about a third are rated poorly on academic performance, attention, and communication by their classroom teachers (Dancer, et al., 1995). Thus academic difficulties and underachievement in this population are more widespread than originally thought. These landmark findings ignited curiosity among researchers to explain why children with UHL were experiencing such broad academic difficulties.

Beyond educational challenges, increased psychosocial problems have also been reported in children with UHL. When compared to their NH counterparts, children with UHL receive a higher proportion of negative teacher ratings on the Behavior Rating Scale (Culbertson and Gilbert, 1986) and the Screening Instrument for Targeting Educational Risk (Most, 2004). Teachers rate children with UHL as having greater difficulty in peer relations, less social confidence, greater likelihood of acting out or exhibiting withdrawn behavior in the classroom, greater frustration and impatience, increased dependence on the teacher, and being more frequently distracted (Culbertson and Gilbert, 1986; English and Church, 1999). Additionally, a higher frequency of negative comments on report cards, failure reports sent home, and teacher-parent conferences have been documented with children with UHL (Keller and Bundy, 1980).

Some researchers have considered that the educational and behavioral problems associated with UHL may have origins in undiagnosed speech and language disorders (Stein, 1983; Bess, et al., 1986; English and Church, 1999). Experimental studies investigating the speech and language abilities of children with UHL have shown mixed results. Some studies have shown delayed speech and language abilities in children with UHL (Peckham and Sheridan, 1976; Young, et al., 1997; Kiese-Himmel, 2002; Sedey, et al., 2002; Borg, et al., 2002; Lieu, et al., 2010) while others have not (Cozad, 1977; Klee and Davis-Dansky, 1986; Kiese-Himmel, 2002). Speech-language delays (e.g., delayed acquisition of two-word phrases) have been detected in very young children (Kiese-Himmel, 2002; Sedey, et al., 2002). In school-aged children, poor scores on language comprehension, oral expression (Lieu, et al., 2010), and narrative skill tests (Young, et al., 1977) have also been found. No published study has yet carefully followed children with permanent UHL longitudinally to see if early-developing language delays persist.

Researchers have also considered that perhaps differences in intelligence could explain academic issues experienced by some children with UHL. Most studies that have investigated general intelligence in children with UHL have found that group mean scores on standard aptitude tests fall in the normal/average range (Keller and Bundy, 1980; Blair, et al., 1985; Culbertson and Gilbert, 1986; Niedzielski, 2006). Some studies have reported that children with UHL who are at risk academically (Klee and Davis-Dansky, 1986) or have more severe degrees of hearing loss (Culberston and Gilbert, 1986) tend to have lower, but often still normal intelligence quotient (IQ). In a study of NICU graduates with hearing loss, children with UHL intriguingly showed significantly lower IQs than their bilateral hearing loss counterparts (Martinez-Cruz, et al., 2009), and as a group had IQs in the low-normal range. Subtle differences in intelligence have been linked to the side of hearing impairment. Children with right-sided hearing loss have shown lower levels of verbal intelligence, whereas those with left-sided hearing loss impairment have shown lower levels of non-verbal intelligence (Jensen, et al., 1989; Niedzielksi, 2006). Currently there are a lack of data to support the idea that academic difficulties experienced by children with UHL are due to intelligence differences.

There is no doubt that unilateral auditory deprivation affects the normal development of the central auditory system. Neuroscience studies have revealed cortical reorganization and differences in brain network interconnectivity in monaurally deaf subjects using fMRI technology (Scheffler, et al., 1998; Schmithorst, et al., 2005; Tibbets, et al., 2011). Neural reorganization may point to explanations for academic difficulties experienced in this population (Propst, et al., 2010). Research is greatly needed to evaluate the effects of early amplification on neural reorganization in children with UHL.

The looming question now is: Why are children who have one normal-hearing ear at risk for such a broad spectrum of developmental challenges? Researchers have theorized that several patient factors may correlate to educational difficulties such as early age of onset of hearing loss, a severe-to-profound degree of hearing loss (Oyler, et al., 1988; Watier-Launey, 1998; English and Church, 1999), right-ear impairment (Oyler et al., 1988; Jensen, et al., 1989), and lower IQs (Bess and Tharpe, 1984), but presently there is a lack of evidence to support any real predictive power of these factors. Answers to questions regarding the bases for the developmental challenges experienced in this population may lie in the lack of binaural auditory processing abilities in these listeners.

1.5 Lack of Binaural Hearing

Listening with two ears is important for everyday communication, particularly in challenging acoustic environments (Licklider, 1948; MacKeith & Coles, 1971; Bronkhorst and Plomp, 1989). The normal auditory system constantly compares auditory input arriving at the two ears, taking advantage of interaural difference cues (both in intensity and timing) to help the listener localize sounds and understand speech in the presence of noise. Individuals with UHL are largely unable to take advantage of interaural cues to help them navigate complex listening environments. Thus, they have shown deficits on tasks that rely on binaural processing, namely sound localization and speech understanding in noise (Gatehouse & Cox, 1972; Bess, et al., 1986; Slattery & Middlebrooks, 1994; Ruscetta, et al., 2005; Linstrom, et al., 2009).

Listeners with NH are able to navigate multisource environments dominated by energetic maskers, where masking occurs due to an overlap of excitation patterns between the masker and target stimuli in the auditory periphery (Durlach, et al., 2003), by using interaural intensity and timing cues to detect the target signal. Listening to speech in the presence of steady white noise is an example of a condition dominated by energetic making. When the target and masker stimuli are spatially separated, one ear is always afforded a better signal-to-noise ratio (SNR) than the other – this is known as the head shadow or better ear effect. This effect is strongest at higher frequencies. For adult listeners with NH, interaural level differences associated with spatially separating an interfering masker from the target can improve speech recognition thresholds (SRTs) by 3 to 8 dB, depending on the acoustical environment and azimuth differences between the speech and masker signals (Bronkhorst & Plomp, 1988). Aside from the head shadow intensity-related effect, each ear receives the target and masker signals at slightly different times. For example, if a masking noise was presented from a loudspeaker at 60° azimuth (i.e., facing the right ear) the noise would reach the subject's right ear a few hundred milliseconds before the left ear, whereas if the masking noise was presented from 0° azimuth it would reach the right and left ears simultaneously. Comparison of interaural timing differences between the two ears contributes to an effect known as binaural unmasking, which is greatest for low frequency sounds. For NH adult listeners, interaural timing differences associated with spatially separating an interfering masker from the target can improve SRTs by 4-5 dB, depending on the acoustical environment and azimuth differences between the speech and masker signals (Bronkhorst & Plomp, 1988). When the target and masking signals originate from different spatial locations, as opposed to being co-located, NH listeners demonstrate improved speech recognition performance – an effect known as spatial release from masking (SRM), which is due to both head shadow and binaural unmasking.

Lacking the ability to use interaural timing and intensity cues to their fullest extent, adults with UHL have exhibited clear deficits understanding speech (word and sentence recognition) in the presence of noise when compared to NH listeners (Tonning, 1971; Sargent, et al., 2001; Welsh, et al., 2004), especially in conditions when noise is directed towards the subject's normal-hearing ear. In this case a poor SNR may occur at the better, and sometimes only, hearing ear resulting in significant decreases in performance. Furthermore, in all spatial listening conditions subjects with significant amounts of UHL, especially in the low frequencies, are unable to benefit from binaural unmasking. Although there are only a few published studies conducted with children with UHL, deficits in speech recognition in spatial masking conditions have been established, interestingly, even in the most favorable conditions of speech being directed towards their good ear and noise towards their impaired ear (Bess, et al., 1986; Bovo, et al., 1988; Ruscetta, et al., 2005). Speech recognition studies with children with UHL to date have largely employed steady-state, energetic-type maskers (e.g., cafeteria noise), limiting our understanding of how children function in more realistic environments, which include fluctuating, real-speech maskers that may posses informational as well as energetic masking properties.

In multisource environments dominated by informational masking (masking that occurs because the masker and target stimuli are qualitatively similar and are easily confusable with one another), individuals with NH achieve greatest speech perception performance when the target and masking signals originate from different spatial locations, as opposed to being co-located, an effect known as spatial release from informational masking (Freyman, et al., 1999, 2001; Arbogast, et al., 2002, 2005; Hawley, et al., 2004; Brungart and Simpson, 2007). The measured SRM is considerably larger than what would be explained by the head shadow and binaural unmasking alone and is considered to be heavily mediated by central mechanisms (Freyman, et al., 1999).

Spatial unmasking has been observed in both adults and children as young as three years of age with NH (Litovsky, 2005; Garadat and Litovsky, 2007; Ching, et al., 2011; Lovett, et al., 2012; Schaefer, et al., 2012). The amount of SRM (measured in dB) depends on several factors, such as the number of sources, type of interfering sources (Hawley, et al., 2004), and room acoustics (Marrone, et al., 2008), but can be as large as 12-15 dB in NH adults. Normal-hearing children consistently demonstrate SRM ranging from 3-11 dB, depending on the listening environment (Garadat and Litovsky, 2007; Johnstone and Litovsky, 2006; Litovsky, 2005; Vaillancourt, et al., 2008; Van Deun, et al., 2010; Lovett, et al., 2012).

While some studies have shown SRM to increase with age (Vaillancourt, et al., 2008; Van Deun, et al., 2010), others have found similar amounts of SRM across age (Litovsky, 2005; Lovett, et al. 2012; Ching, et al., 2011; Schafer, et al., 2012). Developmental differences observed in SRM across these studies may be due to the age range of subjects, masker types employed (noise versus speech), and/or large variability seen between subjects. A few studies have discovered a significant interaction between age and masker type (e.g., spectral versus temporally modulated maskers) (Johnstone and Litovsky, 2006; Hall, et al., 2012). To date, most studies on SRM in children have utilized asymmetrical masking paradigms, where the masker is presented from one side loudspeaker positioned at ±90 degrees azimuth. Few studies have employed a symmetric masking paradigm, where maskers are presented from speakers positioned on both sides of the subject (Ching, et al., 2011). Furthermore, most studies along this line of research that have utilized real-speech maskers have done so using adult speakers. The current study will extend the knowledge base regarding the developmental effects of masked sentence recognition abilities in school-age children using an ecologically valid masker composed of child talkers in a variety of spatial configurations.

When compared to performance of listeners with NH, less SRM has been observed in adults (Marrone, et al., 2008) and children with bilateral hearing loss (Ching, et al., 2011; Misurelli and Litovsky, 2012; Hall, et al., 2012). In a recent study, Rothpletz, et al. (2012) also demonstrated that adults with UHL did not benefit to the same extent as subjects with NH from spatially separating the target signal from an informational masker. The small benefit seen in the UHL subjects, in the most favorable conditions, could be solely explained by the head shadow effect. To date, no studies examining spatial release from informational masking have been conducted with children with UHL.

Poor speech understanding in the presence of noise is not a mere fabrication of laboratory techniques. Both teenagers and adults with UHL have reported embarrassment, annoyance, confusion, and helplessness in communicating with others when there is noise present in everyday listening environments (Giolas and Wark, 1967). Individuals with UHL have also reported being excluded from conversations with multiple speakers and simply avoiding social situations with background noise (Wie, et al., 2010). Given the auditory perceptual decrements measured and reported in complex listening environments, it is puzzling why so few patients with UHL receive audiological intervention. Part of the reason for delayed audiological intervention may be due to the discrepancies in performance results obtained in the clinic versus those experienced in the real world. Clinical testing is not representative of real-world listening situations and children with UHL typically perform very well in clinical evaluations (with their NH ear), which may lead to hesitation to recommend amplification. Perhaps a different result would occur if clinical testing protocols were expanded to be more inclusive of real-world listening situations, such as those where speech is directed towards the impaired ear and noise is directed towards the normal ear.

1.6 Clinical Assessments

Basic auditory detection and speech understanding capabilities of children with UHL are routinely assessed during traditional audiological evaluations, which generally include pure-tone audiometry and speech recognition in quiet measures. Using standard pure-tone audiometry, hearing thresholds in both the impaired and normal ear are monitored for any potential progression, typically on an annual basis. Additionally, age-appropriate word recognition tests (e.g., WIPI, PB-K, NU-6) are administered to each ear separately, with no competing noise (with the exception being when masking is required due to crossover). Pure-tone audiometry and speech understanding in quiet measures hold certain diagnostic merit, but they unfortunately are poor predictors of everyday listening performance. The burdens of listening with one ear are not accurately captured in routine audiological assessment. Even more concerning is that performance on these tests in the clinic is often misinterpreted as hearing that is “good enough” to support speech and language development and daily communication. Furthermore, the aforementioned clinical tests are unable to accurately predict which UHL patients are most at-risk for developmental delays and educational challenges. This “discrepancy” begs the question, “If audiologists evaluated children in more naturalistic listening conditions, would results be more predictive of real-word function?” There is a clear need to bring clinical assessments into line with the listening challenges faced by children in their everyday lives. Perhaps testing that more accurately simulates a classroom environment would help do so.

1.7 Classroom Acoustics

Unlike the ideal listening environment found in audiology clinics, real world spaces are full of competing signals and reverberation, which make for complex listening environments. Primary school classrooms in particular are a perfect example of complex listening environments. In 2001, Picard and Bradley reviewed published ambient noise levels and reverberation times in classrooms (preschool through higher education settings) and their potential effects on speech intelligibility. Reported noise levels in traditional classrooms ranged from 41.9 dBA (junior high classroom) to 75 dBA (kindergarten classroom). Noise levels generally decreased as grade level increased. Typical SNRs (i.e., the relative strength of the teacher’s voice compared to the background noise in the classroom) in regular occupied classrooms ranged between +3 and +9.5 dB (second grade through junior high). Given these SNRs we can expect eight-to-12 year-old children with hearing loss to understand approximately 60% of monosyllabic words without visual cues (Finitzo-Hieber and Tillman, 1978). The American Speech-Language and Hearing Association (ASHA) recommends SNRs in the classroom be at least +15 dB at the child’s ears, a recommendation that is clearly not often achieved in typical classrooms (Picard and Bradley, 2001).

It is well understood that children with hearing loss require more advantageous SNRs to achieve the same level of speech understanding as their NH, age-matched peers (Litovsky, 2005; Johnstone and Litovsky, 2006; Garadat and Litovsky, 2007). In one published study, children with severe to profound UHL were found to require a 2-9 dB improvement in SNR when listening to speech presented in multitalker babble to achieve comparable performance to NH peers (Ruscetta, et al., 2005).

Because poor classroom acoustics can adversely impact all children’s educational performance (Boman, 2004; Dockrell and Shield, 2006; Evans, 2006), standards have been created to identify limits on the acceptable levels of background noise and reverberation times in classrooms. The American National Standards Institute (ANSI, 2010) recommends that the maximum background noise level in an unoccupied medium-sized classroom not exceed 35 dBA regardless of the age of the students utilizing the room. However, as it is well understood that speech perception in noise abilities do not fully mature until the age of 18 years (Elliot, 1979), Picard and Bradley (2001) have provided age-weighted guidelines for classroom ambient noise levels, thought to support both acceptable and ideal levels of speech intelligibility (see Table 1). It is important to note that the maximum noise values outlined below are far lower than those reported in the literature. Additionally, these recommended noise levels are lower than those recommended in the ANSI standards for children with hearing loss and younger children with NH.

Table. 1. Estimated maximum ambient noise levels for unoccupied and occupied quiet classrooms (dBA)

(Adapted from Table 8 from Picard and Bradley, 2001)

Age (years)	ACCEPTABLE (appropriate for children with normal linguistic abilities)	IDEAL (appropriate for children with abnormal linguistic abilities, like many children with HL)
12+	40	33
10-11	39	32
8-9	34.5	27.5
6-7	28.5	21.5

1.8 Listening Demands of the Classroom

Beyond the challenging acoustics of a classroom, the listening demands required in school are quite high. The hierarchy of auditory skills has been described in the following order (from most basic to complex): 1) detection, 2) discrimination, 3) identification, and 4) comprehension (Erber, 1982). Auditory comprehension, the highest-level skill, necessitates not only excellent basic auditory function (e.g., detection and identification), but also requires additional cognitive processes such as short-term storage and ongoing mental processing of the spoken information. Students' academic success is dependent on their abilities to follow, process, and integrate auditory information spoken both by their teacher and classmates, requiring command of all auditory skill levels.

Studies examining speech understanding during realistic learning activities in typical classroom conditions are limited (Klatte, et al., 2007; Klatte, et al., 2010b; Neuman, et al., 2010). There is recent evidence, however, that complex listening environments (e.g., noisy reverberant spaces) may affect higher order cognitive functions involved in comprehension (Klatte, et al., 2007; Gordon, et al., 2009; Ljung et al., 2009). The theoretical premise is that the effort required to decode a speech signal in unfavorable listening environments may leave fewer resources for other cognitive duties such as short-term memory and comprehension (Klatte, et al., 2010a; Picard and Bradley, 2001). Klatte, et al. (2010b) examined word recognition and listening comprehension in children and adults with NH, while varying masker type and reverberation time. For children, one interfering talker negatively affected comprehension performance moreso than diffuse classroom noise (and to a greater extent in younger versus older children); however, the reverse was true on the word recognition task. The researchers suspected that the speech masker interfered with childrens' short-term memory required for the comprehension task. Interestingly, adults' comprehension abilities were unaffected by the same levels of background noise.

Valente, et al. (2012) assessed sentence recognition and comprehension abilities of children with NH when listening to either lecture or discussion-like material. They found that sentence recognition scores for all subjects remained greater than 95% correct in all listening conditions. However, with similar levels of background noise and reverberation, performance was degraded on comprehension tasks, an effect more pronounced for the youngest subjects. Results such as these support the notion that basic auditory tasks such as word and sentence recognition (as measured in the clinic), even in the presence of noise or reverberation, may underestimate the deleterious effects of poor classroom acoustics on daily auditory comprehension and learning activities.

1.9 Summary and Project Aims

Children with UHL are at significant risk for speech and language delays, academic underachievement, and behavioral issues, yet are routinely underserved audiologically. The origin of their difficulties may very well lie in lack of normal binaural processing abilities. Currently we have a very limited understanding of the speech recognition and comprehension abilities of children with UHL in complex, multisource environments. In order to eventually better serve this population clinically it is imperative that we first more clearly define the problems they face in such real-world listening conditions.

The aim of the current research project was to answer some of the outstanding questions regarding the auditory perceptual skills of children with UHL by comparing their performance to that of NH children of the same ages. To this end, school-aged children with NH and UHL were evaluated in listening conditions typical of the real-world environments in which listeners with UHL have reported significant hearing and communication difficulties. Experiment 1 examined the sentence recognition abilities of children with NH and UHL, while varying masker type (noise and real-speech) and spatial configuration of target and masker signals (co-located and spatially separated). Experiment 2 examined the auditory comprehension abilities of children with NH and UHL in the presence of a real-speech masker at varying SNRs. Data collected from both experiments further our understanding of a) the developmental trajectories of these auditory skills in children with NH and b) the functional consequences associated with asymmetric hearing thresholds in pediatric patients.

1.10 Research Questions and Hypotheses

1.10.1 Overarching Questions

1. What is the developmental trajectory of NH school-aged children's auditory perceptual abilities when listening in classroom-like, noisy environments?

2. How does UHL affect school-aged children's auditory perceptual abilities when listening in classroom-like, noisy environments?

1.10.2 Specific Questions

<u>Specific Question 1:</u> As school-age children develop (from six to 12 years of age), do their masked sentence recognition abilities improve?

Hypothesis 1: Given the well-known effect of age on speech reception thresholds (Elliot, 1979; Byrne, 1983; Litovsky, 2005; Garadat and Litovsky, 2007), it is expected that younger children, both with NH and UHL, will exhibit poorer reception thresholds for sentences (RTS) when compared to older subjects in all listening conditions.

<u>Specific Question 2:</u> Are both children with NH and UHL differentially affected by real-speech and noise maskers?

Hypothesis 2: The majority of research has shown that at equivalent intensity levels, maskers composed of a small number of talkers (i.e., two to three) result in more masking than for noise (Carhart, et al., 1975; Hall, et al., 2002). Thus it is expected that both children with NH and UHL will exhibit higher (i.e., poorer) RTS in the presence of two speech interferers versus speech-spectrum noise masking.

Specific Question 3: Does the availability of spatial differences between the target and masking signals improve performance of children with NH and UHL to similar degrees?

Hypothesis 3: Children with hearing loss, even mild in degree, have demonstrated poorer speech-in-noise recognition abilities than children with NH (Crandell, 1993; Ching, et al., 2011). Research has shown that children with UHL show deficits in speech recognition in noise when compared to their NH peers in most spatially separated configurations (Bess, et al., 1986; Ruscetta, et al., 2005). Thus, children with UHL are expected to achieve poorer RTS than age-matched, NH controls in both co-located and spatially separated conditions.

Hypothesis 4: Research shows that children as young as three years of age with NH perform better when listening in conditions that employ spatial separation between target and masking signals in both asymmetric and symmetric configurations (Litovsky, 2005; Garadat and Litovsky, 2007; Cameron and Dillon, 2007; Ching, et al., 2011; Lovett, et al., 2012). However, adults with UHL do not realize as much of this benefit, especially in conditions when the noise is directed towards the subject's impaired ear (Ruscetta, et al., 2005). Therefore, it is hypothesized that SRM benefit will be realized by all children, but in fewer conditions and to a lesser degree by children with UHL.

Specific Question 4: Does a real-speech masker differentially affect comprehension abilities of children with NH and UHL?

Hypothesis 5: It is well understood that children perform more poorly than adults on a variety of speech-perception measures in noise (Finitzo-Heiber and

Tillman, 1978; Elliot, 1979; Nitrrouer and Boothroyd, 1990). Limited evidence suggests that auditory comprehension performance may be more deleteriously affected by poor acoustics than speech recognition (Klatte, et al., 2010b; Valente, et al., 2012). Thus it is expected that as SNR becomes more challenging, auditory comprehension performance will decrease for both children with NH and UHL.

Hypothesis 6: Children with UHL have demonstrated poorer scores on tests of language comprehension and oral expression when compared to normal-hearing peers (Lieu, et al., 2010). They also exhibit abnormal narrative skills (Young, et al., 1977) and specific academic difficulties related to reading comprehension and vocabulary (Blair, et al., 1985). If these findings also translate to auditory comprehension skills, it is hypothesized that children with UHL will exhibit poorer auditory comprehension abilities compared to NH controls in all listening conditions.

CHAPTER 2

METHODS

2. 1 Subjects

A total of 59 subjects participated in the current research project. Thirty-five children with NH and six children with UHL aged six to 12 years, were recruited from local hospitals, schools, childcare facilities, and community organizations to take part in the study. In addition, 18 young, normal-hearing (NH) adults were recruited from the University of Massachusetts Amherst. Subjects were stratified into four experimental groups: 1) young adults with NH (NH-A), 2) children with NH (NH-C), 3) children with UHL who do use of amplification (UHL-U) and 4) children with UHL who routinely use of amplification (UHL-A).

To gain information about pediatric subjects' family, developmental, medical, hearing, and academic history, a parent/guardian was asked to complete a short questionnaire (see Appendix G for Parent Questionnaire), while his/her child participated in the experimental tasks. Pertinent subject information gathered from this questionnaire will be discussed below.

2.1.1 Normal-Hearing Adults (NH-A)

Eighteen young adults (17 females) with NH were enrolled in the study. Subjects' average age was 21 years, with a range equal to 19 to 28 years. All subjects demonstrated hearing within normal limits (hearing thresholds ≤ 15 dB HL 250-8000 Hz bilaterally) as measured by conventional pure tone audiometry

Additionally, all subjects demonstrated recorded word recognition performance ≥ 90% correct bilaterally.

2.1.2 Normal-Hearing Children (NH-C)

Thirty-five children with NH (19 females and 16 males) were enrolled in the study. Subjects' average age was nine years old (9;0), with a range equal to 6;0 to 12;10 (years; months). All children were native English speakers; two children were also reportedly competent in other languages (Portuguese and Ukranian). Additional demographic information about subjects can be found in Appendix A. All subjects demonstrated hearing within normal limits as measured by conventional pure tone audiometry (hearing thresholds ≤ 15 dB HL 250-8000 Hz bilaterally). Additionally, all NH control subjects demonstrated recorded word recognition performance ≥ 90 % correct bilaterally.

All NH pediatric subjects passed the newborn hearing screening conducted at birth. Five children had a history of middle ear infections; all were treated with antibiotics. No report of middle ear surgeries was reported for any NH subjects.

By and large, the NH subjects were healthy, typically developing children. All but three of the subjects were born full term. One premature subject was born six weeks early and two subjects, a pair of twins, were born four weeks early. Four subjects were treated in the Neonatal Intensive Care Unit (NICU) following birth. Two of the subjects who were treated in the NICU were born premature. One child was treated for respiratory issues and jaundice. The other was treated for feeding issues. For the two other subjects who received treatments in the NICU, one received treatment for jaundice and the other received a blood transfusion. Seven children received early intervention services before three years of age. Six of these children received speech-language therapy services and one child received physical therapy services for torticollis. Only one child was ever diagnosed with a developmental delay and this was in the area of speech-language development, for which the issues resolved by five years of age. All NH subjects passed a standardized language screening measure (CELF-5). Three children had medical diagnoses, which were unrelated to speech and hearing abilities: motor ticks, hypermobility of the feet and hands, and convergence insufficiency.

Information about each subject's academic history was collected via the Parent Questionnaire. In general, most parents had positive things to report about their children academically. No parents rated their child's academic status as "below average." Parents of 16 children reported no subject areas needing improvement. None of the subjects had ever repeated a grade. Four children had or were currently receiving accommodations or special education services through either a 504 Plan or Individualized Educational Plan (IEP). Two subjects received speech-language services before the age of five. Two additional students were reportedly receiving accommodations for extended test time (for hand fatigue and convergence insufficiency). Only two parents (6%) reported academic concern for their child.

2.1.3 Unilateral Hearing Loss - Unaided (UHL-U)

Four children with congenital UHL who did not routinely use some form of personal amplification enrolled in this study. Unilateral hearing loss was operationally defined as NH in one ear (air conduction thresholds ≤ 15 dB HL from 250-8000 Hz) and hearing loss in the other ear (air conduction thresholds ≥ 20 dB HL at two or more frequencies). These subjects had not trialed or used a personal hearing device for more than one month within the past year, with the exception of an FM system in the classroom. Two subjects participated in the experiment unaided, without using a hearing device, despite being fit with a traditional hearing aid (8_U* and 10_U). These two subjects had ≤ one month of device use; subject 10_U was a non-compliant hearing aid user (i.e. was fit with a hearing aid, but refused to wear it). One subject participated in the experiment twice, first without hearing her hearing aid (8_U*), although she had been using her newly fit hearing aid for one month at the time of testing, and then later with her hearing aid (9_HA2*). The two test dates were separated by nearly seven months. This subject is always denoted with an asterisk in the both the text and figures for ease of identification.

2.1.4 Unilateral Hearing Loss - Aided (UHL-A)

In addition to the unaided subjects, three children with congenital UHL who routinely used some form of personal amplification enrolled in the study. Subjects in this group utilized either a traditional hearing aid or a CROS hearing aid system (see Table 2). Demonstration of consistent device use per child and parent report (at least eight hours a day, five days a week for the past two months) was required in order for a subject to be included in this group. All hearing devices were examined prior to use in the study to confirm good working order (hearing aid verification procedures are described in detail under Measures of Global Functioning: Audiological). All children who were fit with a hearing device were fit at a late age, average age = 7;11, range = 4;2- to 10;10 (see Table 2). This far exceeds the goal of six months set by the Joint Committee on Infant Hearing. However, two of the three aided subjects were also diagnosed at a later age (three and one half to four years of age). Their losses were likely progressive in nature given both children passed their newborn hearing screenings.

Table. 2. Audiological information for UHL subjects

	AUDIOLOGICAL								
Subject Code	**Newborn Hearing Screening**	**Age at Diagnosis (years; months)**	**Imaging?**	**Etiology**	**Type of HL**	**Degree of HL**	**Side of HL**	**Right Ear PTA**	**Left Ear PTA**
6_U	Refer	0;4	MRI	Absent VIIIth nerve	Sensorineural; Audtory Neuropathy Spectrum Disorder	Severe to Profound	Left	-2	110
8_U*	Pass	4;0	MRI	Unknown	Sensorineural	Mild to Moderately Severe	Right	60	16
9_U	Refer	0;3	Yes *(type uknown)*	Connexin 26	Sensorineural	Mild	Left	15	26
10_U	Pass	8;11	No	Unknown	Sensorineural	Slight to Mild	Left	11	26
9_HA1	Refer	0;6	Yes *(type uknown)*	EVA	Sensorineural (although presents as mixed)	Moderate to Moderately Severe	Left	6	58
9_HA2*	Pass	4;0	MRI	Unknown	Sensorineural	Mild to Moderately Severe	Right	55	10
11_CROS	Pass	3;6	MRI; CT	EVA	Sensorineural (although presents as mixed)	Moderate to Profound	Right	68	0

***Same Subject**

AUDIOLOGICAL CONTINUED								
Subject Code	**Hearing Aid (HA) Recommendation?**	**Age at HA Fitting (years; months)**	**Type of Hearing Device Trialed**	**Type of Hearing Device Currently Used**	**HA use (up to test date)**	**Device Compliance (Days and hours/week)**	**Otitis Media?**	**Middle Ear Surgeries**
6_U	Yes	N/A	None	None	-	-	Yes	No
8_U*	Yes	7;10	Hearing Aid	Hearing Aid	*1 month*	7 days/12 hours	No	PE tubes
9_U	No	N/A	None	None	-	-	No	No
10_U	Yes	10;10	Hearing Aid	Hearing Aid	*2 weeks*	0 days/0 hours	No	No
9_HA1	Yes	8;11	Hearing Aid	Hearing Aid	2 months	6 days/14 hours	No	No
9_HA2*	Yes	7;10	Hearing Aid	Hearing Aid	7 months	7 days/13 hours	No	PE tubes
11_CROS	Yes	4;2	Hearing Aid CROS	CROS	11 months	5 days/10 hours	Yes	No

***Same Subject**

Legend Key for Abbreviations

HL = hearing loss
MRI = magnetic resonance imaging
CT = computed tomography
EVA = enlarged vestibular aqueduct
PTA= pure-tone average (500, 1000 & 2000 Hz)
PE tubes = pressure equalization tubes

2.1.5 All Unilateral Hearing Loss Subjects (UHL-U and UHL-A)

Of the six subjects with UHL, four were female and two were male. Subjects' average age was nine years (9;4), with a range equal to 6;10 to 11;10. All children were native English speakers; one child was reportedly additionally fluent in French. Additional demographic information about subjects can be found in Appendix B.

Information about pediatric subjects' developmental history was collected via the Parent Questionnaire (see Table 2, also refer to Appendix B). Half of UHL subjects passed the newborn hearing screening. Those who were referred for additional testing following the screening had a diagnosis at or before 6 months of age (average = four months). The three children who passed their screening were diagnosed at a much a later age (average = 66 months; range = 42-107 months). Upon detection of hearing loss, all but one child underwent diagnostic imaging including an MRI scan (n=2), MRI and CT scan (n=1), both (n=1), or a scan whose type was unknown to the parent (n=2). For four children, etiologies were identified and included an absent VIIIth nerve (n=1), connexin 26 (n=1), and enlarged vestibular aqueduct (n=2) in two subjects. For the remaining two children, the hearing loss was of unknown etiology. All six children had sensorineural hearing loss, although the hearing loss of the two subjects with diagnoses of enlarged vestibular aqueduct presented as mixed. Hearing losses ranged from mild to profound in degree (see Appendix C for individual audiograms). Half of the subjects had hearing loss in their right ear. Two children reportedly had a history of middle ear infections (no more than a few episodes reported), but were treated solely with antibiotics. Furthermore, a parent of one subject (8_U*/9_HA2*) reported history of middle ear surgeries for PE tube placement, yet no episodes of otitis media were reported. That subject did not have PE tubes at the time of testing. Report of PE tube placement in the absence of middle ear dysfunction is certainly counterintuitive. Questions regarding accuracy of parent report should be considered.

All but one UHL subject was born full term. The one premature subject was born seven weeks early. That child was the only UHL subject who was treated in the NICU following birth. Half of the children (n=3) received services through early intervention programs before three years of age. Four children had other medical diagnoses: ventricular septal defect and autism (6_U); atrioventricular septal defect and attention deficit and hyperactivity disorder (ADHD) (10_U); scoliosis (9_HA1); asthma and thyroid nodules (11_CROS). The subject with autism was diagnosed with pervasive developmental disorder – not otherwise specified (PDD-NOS). This child was largely affected by social anxiety and his disorder did not inhibit him from successfully completing all of the experimental tasks.

All but one subject with UHL was receiving special school services via a 504 Plan or Individualized Education Plan. Common services included preferential seating, FM system use, speech-language therapy, and educational audiology services. No subjects had ever repeated a grade, but three parents (half of subjects) reported academic concerns for their children.

Table. 3. Demographic and developmental information for UHL subjects

	DEMOGRAPHIC		DEVELOPMENTAL				
Subject Code	**Age (Years;Months)**	**Sex**	**Born Full Term or Premature?**	**NICU Treatments**	**EI Services**	**Developmental Delays**	**Other Diagnoses**
6_U	6;10	M	Premature (7 weeks early)	G-tube Double hernia repair	SLP (2x/ week) OT (1x/ week)	Speech-langauge Social-emotional	Autism (PDD-NOS) VSD
8_U*	8;9	F	FT	None	none	None	None
9_U	9;5	F	FT	None	SLP (1-2x/ week)	None	None
10_U	10;10	M	FT	None	none	None	ADHD Partial AVCD
9_HA1	9;2	F	FT	None	PT (2x/ month)	None	Scoliosis
9_HA2*	9;4	F	FT	None	none	None	None
11_CROS	11;10	F	FT	None	none	None	Thyroid nodules Asthma

***Same Subject**

Legend Key for Abbreviations

NICU = neonatal intensive care unit
EI = early intervention
M = male
F= female
FT= full term
SLP = speech-language pathology
OT = occupational therapy
PT = physical therapy
PDD-NOS = pervasive developmental disorder - not otherwise specified
VSD = ventricular septal defect
AVSD = atroventricular septal defect
ADHD = attention deficit and hyperactivity disorder

2.1.6 Exclusionary Criteria

Subjects were excluded from the current study if any of the the following criteria were met:

- Had a diagnosis of a developmental disability or neurological disorder that would potentially affect their hearing or cognitive development.
- Had below average intelligence (by parent report).
- English was the child's second language (Crandell and Smaldino, 1996).
- Received a refer result on the CELF-5 language screening measure (UHL subjects excluded from this criteria).
- Had abnormal tympanometry results defined as a type B or C Tympanogram (see Table 1).
- The reported hearing status was not confirmed through audiological assessment (e.g., a child with reportedly NH found to have hearing loss).
- Obtained a word recognition score in quiet < 90% correct (for ears with NH thresholds).

A total of five children were excluded from the study due to one of the above criteria. Reasons included active middle ear pathology (n=2), previously unknown bilateral hearing loss (n=1), diagnosis of ADHD (n=1), and a refer result on the CELF-5 language screening test (n=1).

2.2 Test Sites

Subjects participated in the study at one of two testing locations, either the Center for Language, Speech, and Hearing at the University of Massachusetts Amherst (Amherst, MA) or at the Audiology Clinic at the University of Massachusetts (UMass) Memorial Medical Center (Worcester, MA). See Appendix D for detailed information about the audiological equipment and test room used at each testing site. Establishing a testing site in both western and central Massachusetts helped to improve participant access. Subjects with NH participated at the test site in Amherst (n = 53), while subjects with UHL participated at the test site in Worcester (n =6).

2.3 Experimental Apparatus

For all listening measurements (hearing test, Experiment 1, and Experiment 2), subjects sat in a child's wooden chair (seat was 13.5" inches from the floor) centered in a sound-treated room (see Appendix D for specifications). Three loudspeakers (Yamaha MSP3 powered monitor speaker, see Appendix E for specifications) were positioned 38" from the floor (the expected ear-level height of subjects), at a distance of one meter from the center of the subject's head, at angles of -60° (i.e., left), 0°, and +60° (i.e. right) azimuth relative to the participant on the horizontal plane. Permanent markings designating the placement of the chair and speaker stands were made on a canvas mat, which was rolled out prior to experimental setup to ensure consistency between subjects.

Custom Matlab software (MathWorks, Natick, MA), which controlled Experiments 1 and 2, was executed on a laptop computer (MacBook Pro) inside the test booth. The software was used to present the stimuli and to score subjects' responses for the main listening experiments. The experimenter maintained control of the computer program throughout the study, manually advancing experimental trials. The experimenter sat on the floor inside the test booth just behind and to the right of the subject. The stimuli were retrieved from the computer's hard disk, converted to an analog signal by an external eight-channel 24-bit/ 96k Hz digital-to-analog (D/A) converter (ESI Gigaport HD+, Leonberg, Germany), and then sent to one, two, or all three of the previously described loudspeakers. The D/A converter was connected to each of the loudspeakers with a RCA plug to ¼-inch phone plug cable.

2.3.1 Calibration

Signal calibration was performed daily using a sound level meter and a recording of the speech-spectrum noise (SSN) used in Experiment 1. A digital-display sound-level meter (RadioShack) was set to measure the level of the calibration signal using A-weighting with a slow response. The sound level meter was attached via a hook and loop fastener (often referred to as the brand name product Velcro) to an adjustable speaker stand set to a height of 38" from the ground, in substitution for center of the listener's head. A repeated loop of SSN (matched in long-term spectrum and root mean square (RMS) level to the speech stimuli used in Exp. 1) was played from the three loudspeakers sequentially to calibrate each separately. The attenuators located on the loudspeakers were adjusted until the level reached 55 dBA for each loudspeaker. Once observed, the sound levels were recorded in a calibration log.

2.4 Measures of Global Functioning

2.4.1 Audiological

All subjects underwent conventional pure tone threshold testing prior to participating in the study. To confirm hearing status, pure-tone audiometry was performed using appropriately calibrated equipment (ANSI S3.6-2004) and done so in an audiometric test room (ANSI S3.1-1999), as previously described (see Appendix D for equipment specifications). Air conduction thresholds were measured on all subjects; bone conduction thresholds were measured only for subjects with hearing loss. See individual audiograms for UHL subjects in Appendix C.

Tympanometry (226-Hz probe tone) was conducted on each ear to assess middle ear function. Middle ear pressure, tympanic membrane compliance, and ear canal volume was measured and recorded. Tympanograms were classified by Type (A, A_s, A_d, B, or C), using the norms provided in Table 4 (Margolis and Heller, 1987; Hanks and Rose, 1993). See individual audiograms for tympanometry results for UHL subjects (Appendix C).

Table 4. Tympanogram types

Tympanogram Type	Middle ear pressure (daPa)	Tympanic membrane compliance (cc)	Ear canal volume (cm^3)
A	-150 to +100	0.3 to 1.5	0.4 to 1.0
A_s	-150 to +100	<0.3	0.4 to 1.0
A_d	-150 to +100	>1.5	0.4 to 1.0
B	No peak	No peak	0.4 to 1.0
C	<150	0.3 to 1.5	0.4 to 1.0

Word recognition abilities in quiet were assessed using age-appropriate, recorded 50-word lists (Appendix F). Testing terminated if the child achieved 100 percent correct at 25 words, otherwise all 50 words were presented. Children ages six to eight years old were administered list 1 or 2 of the Phonetically Balanced Kindergarten (PB-K) Test (Haskins, 1949), which utilizes kindergarten-level vocabulary appropriate for lower grade children (Gelfand, 2009). Older children ages nine-12 years were administered list 1 or 2 of the Central Institute for the Deaf (CID) W-22 Test (Hirsh, et al., 1952), that consists of phonetically balanced, commonly reported English words. Each ear was assessed individually (unaided), either under headphones (TDH-50P) or using insert earphones (3M E-A-R Tone 3a Audiometric Insert Earphones), at 30-40 dB SL re: the subject’s PTA (500, 1000 and 2000 Hz) or 50 dB HL (considered within the range of normal conversational speech), whichever was the larger value (see individual audiograms for presentation levels used for UHL subjects in Appendix C). If UHL subjects had sound tolerance issues and were unable to listen at 30-40 dB SL, word recognition testing was conducted at their maximal comfortable level. Normal-hearing subjects were required to achieve ≥ 90% correct in both ears in order to continue participation in the study. Subjects with UHL were required to achieve ≥ 90% correct in their normal-hearing ear to continue participation in the study (see individual audiograms for word recognition results for UHL subjects in Appendix C).

Additional audiological testing was conducted on children with UHL who routinely used a hearing device (UHL-A). First, a third word list was administered with the use of their personal hearing device. One recorded, 50-word list (PB-K or CID-W22) was presented in the sound field at a presentation level of 50 dB HL, considered within the range of conversational speech, from a loudspeaker positioned at 0° azimuth, 1 meter from the subject's head. This additional word recognition testing was conducted to rule out any binaural interference (i.e., significant decrements in speech understanding by recruiting the impaired ear). No UHL-A subjects demonstrated binaural interference. See individual audiograms for word recognition results for UHL subjects in Appendix C.

Hearing devices were evaluated by the experimenter prior to use in the study to confirm good working order. The experimenter performed a visual inspection and listening check of all devices. This informal assessment included: examining as appropriate the earmold, tubing, and hearing device for any damage, presence of moisture, or debris, evaluating the battery charge and ensuring any activated program switches and volume controls were in working order. Additionally the 6 Ling Sounds (Ling, 1976) were produced (/m/, /ah/, /ee/, /oo/, /sh/, /s/) to assess the clarity of live speech.

For traditional hearing aids, probe microphone measurements were performed for soft (50 dB SPL), medium (65 dB SPL), and loud (90 dB SPL) real-speech input. Real-ear aided gain (REAG) responses were compared to DSL v5 prescriptive targets to determine if a hearing aid was providing adequate gain. The two traditional hearing aids used in the study were found to be in good working order and to be appropriately set for their users (see Appendix J for REAG responses). The difference between the target and measured output for soft, medium, and loud speech inputs when averaged across frequency (250-6000 Hz) was 3 dB for 9_HA1 and 2 dB for 9_HA2*.

For the CROS hearing aid system, real-ear insertion gain (REIG) was conducted following the verification protocol described by Pumford (2005). To summarize, reference microphones were placed on both ears, while a probe microphone was inserted into the better ear only. The CROS transmitter and hearing instrument were positioned on both ears and activated. First, the subject's head was turned 45 degrees so that the better ear was facing the real measurement system's loudspeaker. After selecting the hearing device type (e.g., BTE) in the verification system, real-ear unaided response (REUR) for a pink noise stimulus at 55 dB SPL was recorded. Finally, the subject was rotated so that the poorer ear was at a 45 degree angle toward the sound source. After selecting CROS in the verification system, which switches the reference microphone to the side of the transmitter, the real-ear aided response (REAR) was recorded for the same stimulus. The two responses were compared; for a properly working CROS system the two tracings should be nearly identical. The one CROS system used in the study was found to be in good working order (see Appendix J for REAG responses). The difference between the two responses curves when averaged across frequency (250-6000 Hz) was 2 dB.

The time required to complete all audiological measures previously described differed depending on subject group. Fewer audiological measures were required of NH subjects and thus they took approximately 15 minutes to test. Unaided subjects (UHL-U) took approximately 25 minutes to test, whereas aided subjects took approximately 35 minutes to test.

2.4.2 Speech-Language

To screen pediatric subjects speech and language abilities the Clinical Evaluation of Language Fundamentals - Fifth Edition (CELF-5) Screening Test was administered to all subjects (Semel, et al. 2013). The CELF-5 is a quick and reliable screening tool, appropriate for students aged five-22 years, which can help determine if a child is at risk for an undiagnosed language disorder. The test was normed on a sample of 2,380 children, adolescents, and young adults stratified by age, sex, race, ethnicity, geographic region, and primary caregiver education level. The screening test is comprised of the subtests and specific items from the larger CELF-5 Test found to be the most discriminating in identifying children with and without normal language sills. As indicated in the instructions for administration, children aged 5;0 to 8;11 (years: months) were administered items one-26 of the CELF-5 Screening Test which included four subtests: Word Structure, Word Classes, Following Directions, and Recalling Directions. Children aged 9;0 to 12;11 were administered items 15-45 of the CELF-5 Screening Test which included five subtests: Following Directions, Recalling Sentences, Sentence Assembly, Semantic Relationships, and Word Classes. An example test question from the CELF-5 screener is: “Here is one book. Here are two ________.” The child is expected to finish the sentence with “books” or “more books”.

This test was administered in a quiet room. The CELF-5 screener test booklet was placed on a table directly facing the child and researcher. The researcher sat next to the child on his/her better-hearing side. For children with NH, the researcher sat to the right of the child, which was easier since the researcher was right-handed. Test administration of the CELF-5 screener took approximately 15 minutes.

The outcome measure on this screening test is a simple Pass or Refer. Age-based criterion scores are provided in half-year intervals for ages five to six years and one-year intervals for ages seven-21 years. A “Refer” result on this screening test precluded normal-hearing subjects from further participation in the study (which was the case for one subject), but did not for subjects with UHL (one UHL subject, 10_U, referred on the test). Parents were notified of the results and were counseled on the need for comprehensive speech-language evaluation by a licensed Speech-Language Pathologist when a refer result was obtained.

2.4.3 Academic

The Screening Instrument for Targeting Educational Risk (SIFTER) was sent to each pediatric subjects’ classroom teacher. The SIFTER is a short 15-question teacher questionnaire, which is divided into five topic categories: Academics, Attention, Communication, Class Participation, and School Behavior (Anderson, 1989). The SIFTER has been found to be sensitive in detecting significant differences between children with UHL and NH (Dancer, et al., 1995) and was used to gain some insight into subjects' current academic status. An example question from the SIFTER is "How does the student's comprehension ability compare to the average understanding ability of his/her classmates?" The teacher rates the child on a 5-point Likert scale: e.g., 5 (Above), 4, 3 (Average), 2, and 1 (Below). A total of 15 points is possible in each of the five subtests. Each category has its own pass/marginal/fail criteria. Either the researcher or the subject's parent provided the questionnaire to the child's teacher via email, postal service, or hand delivery. Instructions were sent along with the questionnaire as well as a self-addressed stamped envelope (except when corresponding via email) so that the teacher could easily return the completed questionnaire to the researcher. For subjects that participated in the study in the summer or early fall semester (before December 1st), questionnaires were sent to their teacher from the previous academic year. See Appendix H for Cover Letter to Classroom Teachers and Appendix I for the SIFTER questionnaire.

2.4.4 Quality of Life

To assess pediatric subjects' quality of life, the Hearing Environments and Reflection on Quality of Life (HEAR-QL-26) was administered to all subjects. The (HEAR-QL-26) questionnaire is a hearing-related quality of life measurement tool that has been shown to be valid, reliable, and sensitive for children with both UHL and bilateral hearing loss (Umasnksy, et al., 2011). The HEAR-QL-26 is a 26-question questionnaire, appropriate for children 7-12 years old, which assesses three factors: perceived difficulty hearing in certain environments/situations (Environments), impact of hearing loss on social/sports activities (Activities), and impact of hearing loss on the child's feelings (Feelings). Children who routinely use a hearing device were asked to answer the questions the way they hear with their device on. An example question from the questionnaire is, "Is it hard to hear in gym class (Physical Education, PE)?" Children rated their responses on a 5-point Likert scale: Never (5), Almost Never (4), Sometimes (3), Often (2), or Almost Always (1). Scores are transformed to a 0-100-point scale, where higher scores indicate a better hearing-related quality of life. The overall HEAR-QL-26 score is computed as the sum of scores for items on each subscale divided by the number of items completed. The experimenter read each question item aloud to subjects in a quiet room and recorded their responses. Test administration of the HEAR-QL-26 took approximately 5 minutes.

2.5 Experimental Measures

Sentence recognition (Exp. 1) and comprehension abilities (Exp. 2) of school-age children (aged 6-12 years) with UHL, NH, and young adults with NH were tested in a mixed measures design. Experiment 1 always preceded Experiment 2, since data collected in Experiment 1 were subsequently used in Experiment 2.

2.5.1 Experiment 1: Effect of Masker Type and Spatial Configuration of Target and Masker Signals

Experiment 1 was designed to assess subjects' masked sentence recognition abilities in different spatial configurations.

2.5.1.1 Target Stimuli

The Hearing In Noise Test (HINT) was developed to provide an efficient measure of RTS in quiet and in noise in the sound field (Nilsson, et al., 1994). The children's version, the Hearing In Noise Test - Children (HINT-C), is appropriate for use with children aged six to 12 years (Nilsson, et al., 1996). The HINT-C sentence corpus is comprised of 16 equivalent 10-sentence lists (three practice lists + 13 test lists), totaling 160 sentences. Lists are phonetically balanced and equated for naturalness, length, and intelligibility. An example sentence is "The ice cream is melting." The HINT sentences are commonly utilized for both clinical and research purposes. The sentences used for this study were the commercially available recordings, which were recorded by a male professional voice actor. For details regarding stimulus generation see Nilsson, et al. (1994).

2.5.1.2 Masker Stimuli

Two maskers were used in Experiment 1: speech-spectrum noise (SSN) and two-talker child babble (TTB). One 10-year-old girl and one 10-year-old boy were digitally recorded speaking a series of nonsense sentences (e.g., "A shop will frame a dog.") and were sampled at a rate of 44100 Hz. Each talker's recordings were stripped of their pauses, equated in RMS level, and then added together to create 60.05 seconds of continuous TTB.

Speech spectrum noise was taken directly from the HINT-C compact disc. This noise has the same average long-term frequency spectrum as approximately two minutes or 72 continuous HINT-C sentences. The original recording of the semi-random white noise was synthesized at a sampling rate of 20161 Hz, filtered using a custom FIR filter, and scaled to the same root mean square amplitude as the target speech. For additional details regarding stimulus generation see Nilsson, et al. (1994).

2.5.1.3 Procedure

In Experiment 1, each subject listened under eight conditions (see Table 4). The target signal (i.e., HINT-C sentence) was always presented from the front loudspeaker positioned at 0°, while the masker signal (TTB or SSN) and masker location (0°, +60°, -60°, or ±60°) varied. The position of the target and masker signals remained constant through the entirety of a trial. On each trial the masker(s) preceded the target sentence by 100 milliseconds.

Sixteen adaptive trials were run in Experiment 1. In doing so all 16 HINT-C lists were used once and subjects listened to a total of 160 sentences. In noisy conditions, subjects produced a reception threshold for sentences for two adaptive tracks (denoted in Fig. 4 by “2” inside the cell), which were then averaged. For the quiet track, subjects listened to one, 10-sentence list (denoted in Fig. 4 by “1” in the cell). Nilson, et al. (1994) determined that when using one, 10-sentence HINT list the 95% confidence interval is ±2.98 dB for RTS in quiet. When using two, 10-sentence HINT lists the 95% confidence interval is ±1.49 for RTS in noise. The quiet condition was always run first, followed by the first random presentation of the seven, unique noisy conditions. Following a break the subject then listened to the second random presentation of the seven noisy conditions.

Table 5. Number of HINT-C lists presented in each experimental condition in Experiment 1

Spatial Configuration of Target and Masker

		Co-located	Asymmetrical Masking *(masker presented from just one side speaker)*		Symmetrical Masking *(masker presented from both side speakers)*
		Front/ Front	Front/ Impaired *(right for NH)*	Front/ Normal *(left for NH)*	Front/ Impaired *(right for NH)* & Normal *(left for NH)*
Masker Type	TTB	2	2	2	2
	SSN	2	2	2	
	None/Quiet	1			

Spatial Configurations Key:

Front/Front: Target and masker signals presented from the front speaker at 0°

Front/Impaired (right for NH): Target signal presented from the front speaker at 0°. Masker signal presented from one of the side speakers positioned at +60° or -60° (whichever was directed towards their ear with hearing loss). For normal-hearing subjects this was always the right speaker.

Front/Normal (left for NH): Target signal presented from the front speaker at 0°. Masker signal presented from one of the side speakers positioned at +60° or -60° (whichever was directed towards the normal-hearing ear). For normal-hearing subjects this was always the left speaker.

Front/Impaired (right for NH) & Normal (left for NH): Target signal presented from the front speaker at 0°. Masker signals presented simultaneously from both side speakers positioned at +60° or -60°. For the 2-talker masker, the two individual talkers that made up the two-talker babble were spatially separated – one talker presented from each side loudspeaker.

The subjects’ task in Experiment 1 was to repeat back the target sentence – guessing was encouraged if they were unsure (see instructions to subjects in Appendix K). Subjects’ oral responses were judged for correctness by the experimenter. An incorrect response was anything less than 100 percent of the words correctly identified in each sentence. An exception to this rule was made in the current study for the first sentence. If the subject was able to identify all but one of the words over three consecutive trials, the experimenter deemed their response correct and the adaptive run proceeded. The decision to continue after three nearly perfect attempts was guided by the known the effects of priming (Schacter and Buckner, 1998). It is possible that after a subject believes he/she heard has heard the sentence one particular way he/she has almost indefinitely primed their brains for continuing to perceive the sentence that way. Following scoring of the subject's response the experimenter advanced to the next trial or condition using custom Matlab software.

Reception thresholds for sentences were measured in each condition according to the following methodology. For all noisy conditions, the masking signal was held constant at a level of 55 dBA, while the level of target sentences varied based upon the correctness of the previous response. The first sentence was presented either at 45 dBA (-10 dB SNR) for noisy conditions or 15 dBA for quiet conditions. This first sentence was repeated until the subject was able to correctly identify the sentence. The level of the target sentence was increased by 2 dB on each repetition. The level of the target sentences was then increased/decreased (increased if the subject's last response was incorrect or decreased if the subject's last response was correct) in 2 dB steps for sentences two through ten. The original HINT-C adaptive method uses a step size of 4 dB for sentences one to four and 2 dB for sentences five to ten. Smaller step sizes (2 dB) were used initially (sentences one to four) in an attempt to more accurately track the subject's threshold from the beginning of an adaptive run.

Following the completion of a condition, the software automatically calculated the RTS, following the HINT-C protocol. For noisy conditions the presentation levels of sentences 5-10 and the level at which the 11th sentence would have been presented were averaged and then subtracted from the noise level. This calculation approximates the SNR (dB) at which the sentences were correctly identified 50 percent of the time. For the quiet condition, the presentation levels of sentences 5-10 and the level at which the 11th sentence would have been presented were simply averaged to find the RTS in quiet (dBA).

2.5.1.4 Practice

To familiarize subjects with the experimental task, one 10-sentence HINT-C list was presented adaptively from the front loudspeaker in quiet before starting the experimental conditions. Sentences used for practice were not used in experimental conditions.

2.5.2 Experiment 2: Auditory Comprehension

Experiment 2 was designed to assess subjects' auditory comprehension abilities in the presence of TTB at varying SNRs.

2.5.2.1 Target Stimuli

Three short stories (McDonalds, The Shipwreck, and The Dragon, see Appendix L) were taken from the Test of Narrative Language (TNL) (Gillam and Pearson, 2004) to serve as stimuli for Experiment 2. The TNL has been empirically established to have high reliability and validity in assessing narrative comprehension and oral narration skills in children aged 5;0 to 11;11. The test was normed on 1,059 children from 20 different states. The TNL is divided into two subtests: narrative comprehension and oral narration; only stories and comprehension questions from the narrative comprehension subtest were used. Picture cues, which are traditionally used when administering two of the three narrative comprehension stories in the TNL were eliminated so that auditory comprehension abilities could be better isolated. The TNL's narrative comprehension subtest measures the subject's ability to recall and understand information in stories produced by others (e.g., What was the girl's name?). It also measures the ability to make inferences about information that was not explicitly stated in stories (e.g., What was the problem in the story?). For each short story there are 9-11 comprehension questions (see Appendix L). Subjects received one point for each correct response, from which a percent-correct score was calculated for each story.

The stories and corresponding questions were digitally recorded by an adult female talker (age 28) with a standard American English dialect in a double-walled sound-treated booth (IAC 1640). The talker's mouth was positioned approximately 6 inches from a cardioid condensor microphone (Audio-technica AT2020) fit with a 6" nylon mesh microphone pop filter (Gator Essentials). The microphone had a flat frequency response from 20 to 20,000 Hz. The signal was fed to a preamplifier (PreSonus TubePre, Baton Rouge, LA) (see Table 5 for preamplifier settings), then sent to an external sound card (Behringer U-Control UCA202), which was connected by USB to a personal computer (MacBook Pro). The VU meter on the preamplifer was visually monitored during live recordings to avoid any peak clipping. Recordings were made using Audacity, audio-editing and recording software, with 16-bit resolution at a 44100 Hz sampling rate. Each story was edited to remove any noise in between sentences using Adobe Audition. The stories were then scaled to the same overall RMS amplitude using the Adobe Audition software package.

Table 6. Preamplifer settings

Control	**Setting**	**Effect**
Phantom power switch (+48 v)	Engaged	Power was supplied at a constant rate ensuring optimum performance of condenser microphone and that the signal was free of distortion due to insufficient power.
80 Hz rumble filter	Engaged	Eliminated low frequency noise.
Drive potentiometer	Set to 0 dB	
Gain control	Set to approximately 30 dB	Increased the amount of the signal being processed by the preamplifer.

Intelligibility of the recorded stories and questions was verified on a group of young normal-hearing adults. Ten listeners (9 females, mean age = 22 years, range = 21-32 years) with audiometric thresholds ≤ 20 dB HL at octave frequencies between 250 and 8000 Hz participated in verification testing of the stimuli. Subjects were undergraduate students enrolled in a course in the Department of Communication Disorders at the University of Massachusetts Amherst who received extra course credit for their participation. Subjects were seated in a double-walled sound-treated booth (IAC 1604) while they listened to and repeated back the stories (one phrase at a time) and corresponding questions (one question at a time). Stimuli were presented at 60 dBA (ensuring both an audible and comfortable listening level for subjects) via a loudspeaker (Realistic Minimus 7) positioned approximately 1.3 meters from the subject’s head at ear-level height (1.2 meters high). Nearly every word of the recorded stories and questions was repeated back correctly. There were a total of four words that were incorrectly repeated (“puddle” in The Shipwreck Story, “large”, “run”, and “terror” in The Dragon Story); however, none of the words were misperceived by more than one subject.

2.5.2.2 Masker Stimulus

The same speech maskers used in Experiment 1 were employed in Experiment 2. Individual recordings of the two child talkers, which were used to generate the TTB, were spatially separated from each other resulting in each talker being presented from a different side loudspeaker (± 60 degrees azimuth). These maskers were selected to simulate classroom chatter, while a teacher is reading aloud to the class.

2.5.2.3 Procedure

Stories were always presented from the front loudspeaker positioned at 0° azimuth. In noisy conditions, the masking signals were presented from both side speakers positioned at ±60° at a constant level of 55 dBA and always preceded the stories by two seconds. Stories were presented (a) in quiet, (b) at a +6 dB SNR, the average SNR found in occupied regular classrooms (Picard and Bradley, 2001), and (c) at the individualized SNR which produced each subject’s reception threshold for sentences as measured in Experiment 1 (with symmetrical masking). Subjects were asked to verbally answer a set of oral comprehension questions (9, 10, or 11 questions depending on the story) immediately following presentation of each story. See Appendix M for instruction to subjects. Comprehension questions were taken directly from the TNL (Appendix L). Recorded questions were presented from the front speaker positioned at 0° at a level of 55 dBA (considered within the range of normal conversational speech) in quiet. The order of questions was consistent across subjects. The experimenter controlled the presentation of the questions; no time limit was imposed on the subjects' responses. A percent correct score was calculated for the answers to questions from each story.

Each subject listened to three short stories in Experiment 2, one for each of the three experimental listening conditions. Presentation order of the listening conditions always remained constant across subjects: 1) Quiet, 2) +6 dB SNR, and 3) at the SNR that produced each subject's reception threshold from Exp. 1. The three experimental stories taken from the TNL were not of equal lengths. Two of the stories were of similar duration; however, one story was significantly longer than the others. Story one (McDonalds) had 155 words and was recorded in approximately 58 seconds. Story two (The Shipwreck) had 190 words and was recorded in approximately 1 minute 7 seconds. Story three (The Dragon) had 381 words and was recorded in approximately 2 minutes 29 seconds. In order to perfectly counterbalance the stories and listening conditions amongst subjects, 21 subjects would be required to participate in each subject group. In anticipation that subject recruitment of children with UHL would be challenging, an alternative approach was taken. Since the third story (Dragon) was grossly different in length than the first two stories, it was always presented in the listening condition that used the SNR that produced the subjects' RTS from in Exp. 1 in the third position. The other two stories (McDonalds and Shipwreck), however, were varied in presentation order and listening condition. The first half of subjects tested listened to the McDonalds story in quiet followed by the Shipwreck story at +6 dB SNR. The second half of subjects listened to the Shipwreck story in quiet followed by the McDonalds story at +6 dB SNR. The decision to switch the story order was made after initial testing revealed better performance in the +6 dB SNR condition compared to the quiet condition, a counterintuitive result. These findings were interpreted as a likely difference in story content or difficulty of comprehension questions associated with each story and therefore the order was reversed to counterbalance this effect.

2.5.2.4 Practice

To familiarize subjects with the experimental task, subjects listened to a short story ("Rudy and Louis") taken from the CELF-5: Understanding Spoken Paragraphs subtest before listening to the three experimental stories. This story was deemed appropriate for 5-6 year-old children. The practice story was presented from the front loudspeaker (0°) in quiet. Subjects then answered two comprehension questions for this story, which were taken from the CELF-5. These two practice questions were correctly answered by all subjects.

2.6 Order of Events

Before participation in the study began, assent was obtained from subjects aged 6-12 years. Written informed consent was obtained from the parents of minor subjects and from each adult subject. Parents of pediatric subjects were asked to complete the Parent Questionnaire, while their children participated in the experimental tasks. Subjects first completed all audiological measures to confirm hearing status. Following the audiological testing, subjects then participated in Experiment 1, which had a mandatory break at the halfway point. Following completion of Experiment 1, subjects completed Experiment 2. Finally, pediatric subjects were administered the CELF-5 followed by the HEAR-QL. Subjects were offered short breaks after audiological testing, Experiment 1, and Experiment 2. After pediatric subjects completed their required tasks, the researcher then reviewed the Parent Questionnaire with parents and asked follow-up questions if necessary. The SIFTER questionnaire was then given to the subject's parent to pass along to the subject's teacher or the teacher's email was provided to the researcher. Total participation time equaled 60 minutes for NH subjects and 90-120 minutes for subjects with UHL. See Appendix N for a more detailed list of the order of events in a test session.

2.7 Data Analysis

Specific Question 1: As school-age children develop (from six to 12 years of age), do their masked sentence recognition abilities improve?

To assess the effect of age (six to 12 years) on RTS performance of pediatric NH subjects in each listening condition, Pearson product-movement correlations were performed (age in months compared to RTS performance). The strength of the correlation, *r*, as well as statistical significance was reported using a criterion of $\alpha = 0.05$. Subjects' scores were then grouped into bins (by years of age) and average scores and standard errors of the mean were calculated. To determine when pediatric performance became adult-like, average scores in each age group were compared to the adult mean score. To compare developmental trajectories across listening conditions, differences in slopes (dB/year) between RTS functions were compared.

Specific Question 2: Are both children with NH and UHL differentially affected by real-speech and noise maskers?

To assess the effect of masker type (SSN and TTB) on RTS performance of pediatric NH subjects, paired sample t-tests were conducted within each masking configuration using a criterion of $\alpha = 0.05$. For example, for the co-located masking configuration, RTS performance (all NH pediatric subjects included) was compared between masker types TTB and SSN.

To assess the effect of masker type on RTS performance for the six UHL subjects, individual difference scores were calculated and compared across each masking configuration.

Specific Question 3: Does the availability of spatial differences between the target and masking signals improve performance of children with NH and UHL to similar degrees?

To compare the six children with UHL to the 35 NH pediatric subjects, RTS and SRM scores were displayed on a scatterplot along with ±1 standard deviation from the predicted NH age mean for each listening condition. The number of data points from UHL listeners falling outside of these boundaries was compared to the number expected in a normal distribution.

To further facilitate comparison between subjects with NH and UHL, standardized scores for RTS and SRM values were derived using the equation below.

$$\frac{y_i - \hat{y}}{\sqrt{S^2_{pooled}}}$$

Where,
y_i= individual subject's score
$\hat{y}$= predicted value for subject's age
$\sqrt{S^2_{pooled}}$ = average standard deviation for subject's age

In short, individual UHL subject scores were converted to standard deviation units obtained from the NH listeners. In doing so, scores could be compared to a specified distribution of scores (e.g., ±1 standard deviation) of NH subjects. The number of UHL scores falling outside the ±1 standard deviation boundaries for NH subjects was calculated for each masking configuration. The square root of the average variance (across age) was used because differences in variance between age groups were small.

<ins>Specific Question 4:</ins> D Does a real-speech masker differentially affect comprehension abilities of children with NH and UHL?

To assess the effect of age (6 to 12 years) on comprehension performance of pediatric NH subjects in each listening condition, Pearson product-movement correlations were performed. The strength of the correlation, r, as well as statistical significance was reported using a criterion of $\alpha = 0.05$. Subjects' scores were then grouped into bins (by years of age) and average scores and standard errors of the mean were calculated. To compare the effect of listening conditions across all NH pediatric subjects, three pairwise comparisons were made. The Holm's sequential procedure was used to control for familywise error using a criterion α = 0.05. To compare NH pediatric to NH adult performance in each listening condition, Welch's t-tests were performed. Again the Holm's sequential procedure was used to control for familywise error using a criterion (α = 0.05).

To compare the six children with UHL to the 35 NH pediatric subjects, comprehension scores were displayed on a scatterplot along with ±1 standard deviation from the predicted NH age mean for each listening condition. The number of UHL scores falling outside of these boundaries was compared to the number expected in a normal distribution.

CHAPTER 3

RESULTS

3.1 Subject Recruitment and Retention Rates

3.1.1 Adults with Normal Hearing

Following Institutional Review Board (IRB) approval, 21 normal-hearing adult subjects participated in the current study between the dates of October 21, 2014 to November 18, 2014. Data from adult listeners were collected at the University of Massachusetts Center for Speech, Language, and Hearing in Amherst, MA. Three of the adult subjects were excluded from the final data analysis due to methodological issues. Two of these subjects were too tall or heavy to sit in the experimental chair and for one subject Experiment 2 was run in an incorrect order. Only the 18 subjects included in the final data analysis will be reported on further.

3.1.2 Children with Normal Hearing

Following Institutional Review Board (IRB) approval, 46 normal-hearing pediatric subjects participated in the current study between the dates of May 21, 2014 to March 13, 2015. Subjects were run at the University of Massachusetts Center for Speech, Language, and Hearing in Amherst, MA. Four of the participants served as initial pilot subjects. An additional six subjects were excluded from the final analysis: three subjects did not pass their hearing and/or middle ear screening and were subsequently excluded from further testing, one subject chose to discontinue participation during Experiment 1, one subject did not pass the language screening (CELF-5), and one subject was diagnosed with attention-deficit/hyperactivity disorder. Only the 35 subjects included in the final data analysis will be reported on further.

3.1.3 Subjects with Unilateral Hearing Loss

Following Institutional Review Board (IRB) approval, six children with hearing loss participated in the current study between the dates of June 27, 2014 to January 18, 2015. These subjects were run at the UMass Memorial Medical Center in Worcester, MA. One child (8_U*/9_HA2*) participated in the experiment twice, first without and then later with a hearing aid (test dates were separated by nearly 7 months). Four children participated in the experiment unaided (_U). Three children participated in the study while using either their hearing aid or CROS system (_A).

3.2 Screening Instrument for Targeting Educational Risk (SIFTER)

Information about pediatric subjects' academic status was collected via a teacher questionnaire named the SIFTER (Anderson, 1989). For NH subjects, 22 completed questionnaires were returned, yielding a return rate of 66.7%. The return rate of questionnaires differed depending on whether the questionnaire was sent to subjects' current (70%) versus past teachers (50%). A majority of NH students were rated favorably in most content areas. A total of 110 ratings were obtained for the 22 students (22 students x 5 rating areas). Of the 110 ratings, 16 were marginal and another six were failing – these were distributed across ten subjects. Interestingly, of the ten subjects who received a marginal or failing rating in one or more categories by their teachers, only one parent also reported academic concern. For NH subjects, teachers were most likely to rate students as poor, defined as the assignment of marginal or fail ratings) in the area of Communication (41%), followed by Academics (27%), then Attention (18%), and finally Class Participation (14%). No students received anything less than a passing rating in the area of School Behavior (see Fig. 1).

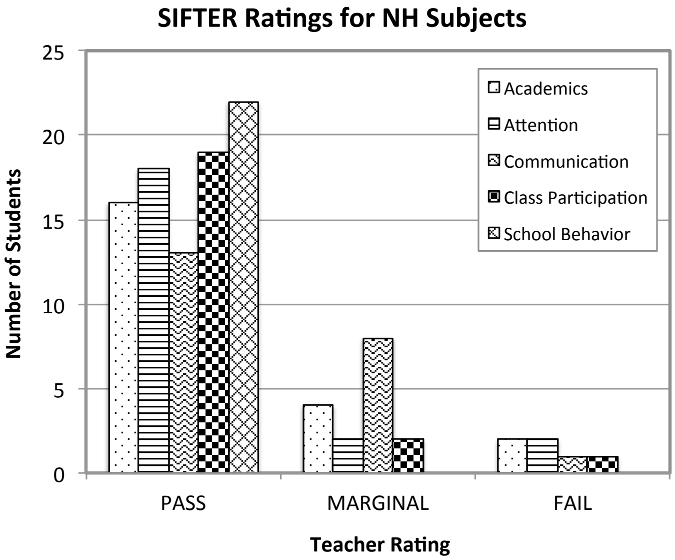


Figure 1. SIFTER ratings for NH subjects for each content area.
The number of NH pediatric subjects who received passing, marginal or failing scores for each content area of the SIFTER.

For subjects with UHL, seven completed questionnaires were returned to the researcher, yielding a return rate of 100%. A majority of students with UHL were rated favorably in most or all content areas (see Fig. 2). However, one student (10_U) was rated as failing in all areas. One child (6_U) received a marginal score in the area of Communication; this was the six-year-old child who had a diagnosis of autism. Additionally, one child (9_HA2*); received a marginal score in the area of Attention, which was a worse score when compared to her passing rating in this area in the previous academic year (8_U*); the questionnaires were completed by two different teachers (i.e., the subject's third and fourth grade teachers). Teachers were most likely to rate UHL students poor (i.e., marginal or fail fatings) in the area of Communication and Attention (28%), which was then followed by Academics, Class Participation, and School Behavior (14%). These results can be compared to those of NH subjects. Subjects with UHL proportionally had better ratings on Communication and Academics, but poorer ratings on Attention and School Behavior. Normal hearing and UHL subject groups had equal ratings on Class Participation.

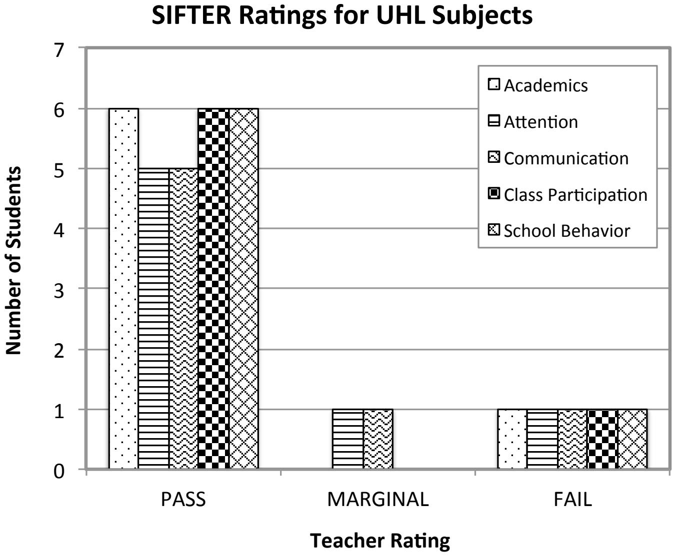


Figure 2. SIFTER ratings for UHL subjects for each content area.
The number of subjects with UHL who received passing, marginal or failing scores for each content area of the SIFTER.

3.3 The Hearing Environments and Refection on Quality of Life (HEAR-QL-26)

Information about pediatric subjects' quality of life was collected via the HEAR-QL-26. It was determined that not all six-year-old subjects were able perform the rating task reliably; HEAR-QL-26 was designed for children ages seven to 12 years old. Any HEAR-QL-26 results from six-year-old subjects whose responses were deemed inconsistent and unreliable by the researcher were excluded from the final analysis (n=3). An example of inconsistent responses would be if a child responded "Almost Always" to the question "Does your hearing make you feel different from everyone else?", but responded "Never" to the question "Do you feel different from others because of your hearing?" The final analysis includes 32 children with NH and seven sets of responses collected from the six children with UHL.

Average results for the different subject groups are shown in Figure 3. Interpretation of mean results between subject groups should be carried out with caution, given the unequal samples sizes between the groups (see Fig. 3 caption), although comparisons within a subject group across the different subscales holds more merit. For subjects with UHL, quality of life (QoL) scores were lowest on the Environments subscale. Questions in the Environments subscale target how subjects' hearing loss affects their perceived ability to listen in adverse listening environments such as classrooms, restaurants, during gym class, and at recess. Following Environments, the Feelings subscale had the second lowest QoL score for subjects with UHL. Questions in the Feelings subscale addresses subjects' emotional response to hearing loss. For example, does their hearing loss make them feel angry, nervous, anxious, timid, or simply different from others? The smallest difference between subjects with NH and UHL was observed on the Activities subscale. Questions in the Activities subscale address how a subject's hearing loss affects their social engagement with their peers. At least for the subjects in the current study, it appears that UHL did not preclude involvement in certain social situations (e.g., attending parties or extracurricular activities). Subjects with NH had relatively high QoL scores in all domains. The lowest scores were obtained in the Environments subscale, similar to subjects with UHL. To compare total scores between subjects with NH and UHL, Welch's unequal variances t-test was performed, which revealed a significant difference between the two subject groups, $t(7) = 4.89$, $p = 0.002$, with NH subjects having significantly higher QoL total scores than UHL subjects.

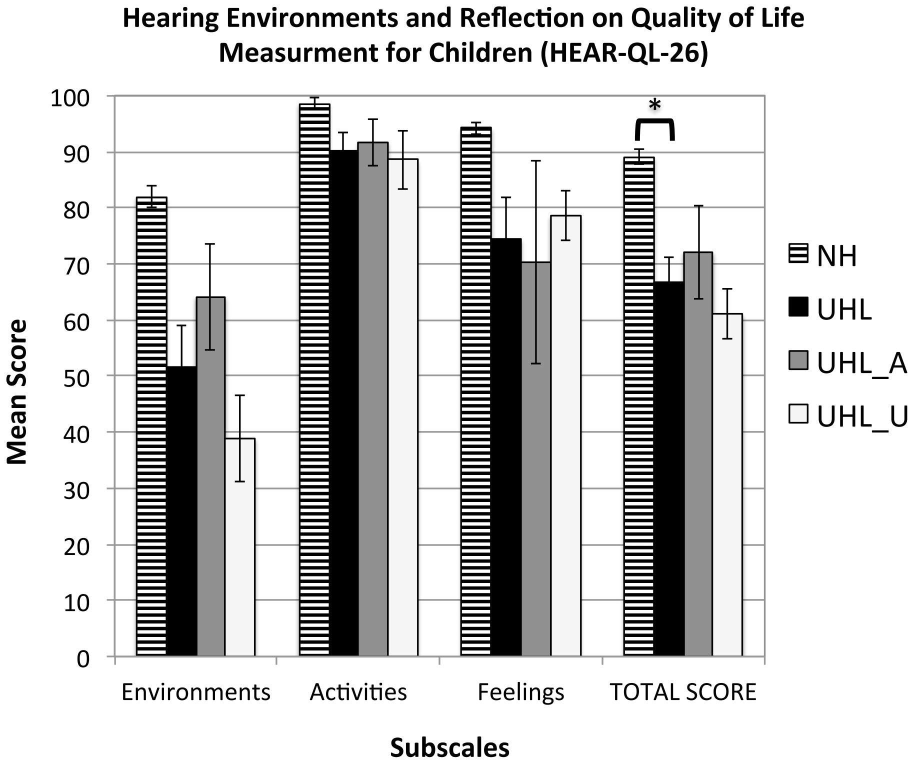


Figure 3. Mean scores plotted as a function of HEAR-QL-26 subscales and total score for each subject group.
UHL group combines subjects from UHL-A and UHL-U groups. Subject group numbers: NH = 32, UHL = 7, UHL-A = 3, UHL-U =4. The error bars denote ±1 standard error of the mean.

To further compare children with UHL to NH subjects across all HEAR-QL-26 subscales, standardized scores were derived using the following equation.

$$\frac{y_i - \bar{y}}{\sigma}$$

Where,
y_i= individual subject's score
$\bar{y}$= NH mean
σ = NH standard deviation
In short, individual UHL subject scores were converted to standard deviation units. In doing so, scores could be compared to a specified distribution of scores (e.g., ±1 standard deviation) of NH subjects.

Standardized scores are shown in Fig. 4. It is clear that a majority of subjects with UHL fell below one standard deviation of the NH subject mean and many subjects with UHL also fell below two standard deviations of the NH mean. A total of four scores (three subscales + one total score) per subject were obtained totaling 28 scores. Of the 28 scores only six fell within the ±1 standard deviation boundaries, four of which were from two children utilizing amplification (9HA1 and 9_HA2*). Results indicate that the children with UHL included in this study have a lower reported quality of life, in all domains (Environments, Activities, and Feelings) when compared to the children with NH. Given the small sample size of the UHL subject group, results would need to be confirmed with a larger data set before generalizing to the larger UHL population.

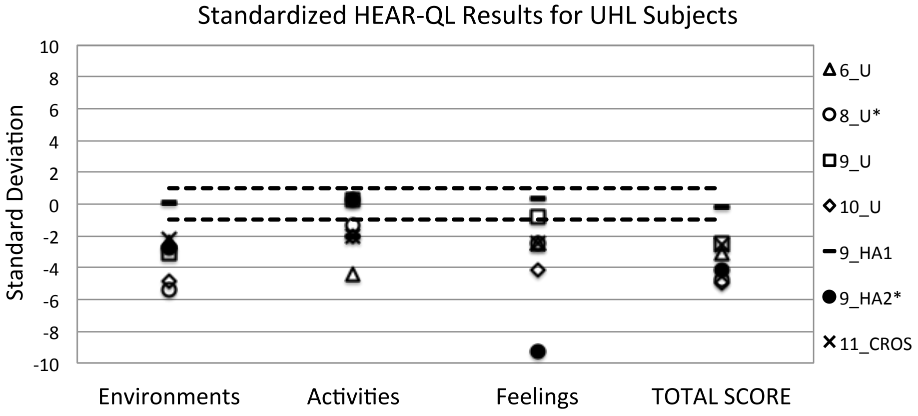


Figure 4. Number of standard deviations from the NH mean for each UHL subject across all HEAR-QL subscales and total score.
Dashed lines demarcate ± 1 standard deviation from the NH mean.

Subject (8_U*/9_HA2*) completed the HEAR-QL-26 twice, once unaided and a second time with a hearing aid; her results are displayed below in Fig. 5. With the exception of the Feelings subscale, QoL scores increased with use of a hearing aid. It is possible the decrease in QoL noted in the Feelings subscale is due to the subject's increased awareness of her hearing loss. Use of a hearing aid certainly makes her hearing loss visible to peers. It is possible that the use of a hearing aid created intrapersonal insecurities and increased feelings of being different compared to her NH peers. These initial results suggest the need for future research in this area of quality of life and point to potential improvements in the Environments and Activities subscales for UHL subjects utilizing a hearing device.

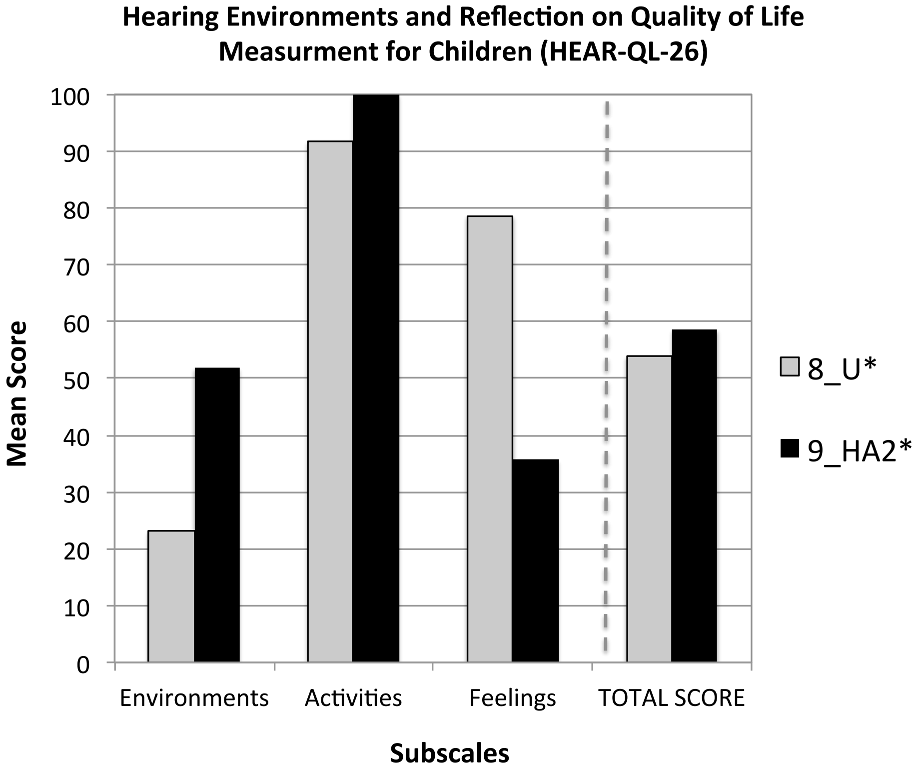


Figure 5. HEAR-QL-26 scores plotted as a function of subscales and total score for subject (8_U*/9_HA2*).

3.4 Experiment 1

3.4.1 Quiet Condition

Reception thresholds for sentences were measured quiet for NH and UHL subjects. Both target and masking signals were presented from the same loudspeaker positioned at 0° (Front/Front).

3.4.1.1 NH Subjects

Reception thresholds for sentences were measured in quiet. Results from subjects with NH are shown below in Fig. 6 – see Appendices Q for individual data. A Pearson product-moment correlation coefficient was computed to assess the relationship between age and quiet RTS. A strong, negative correlation between RTS performance and age was found, *r*(33) = -0.60, p < .001. As age increased from six to 12 years, performance improved (RTS decreased) by more than 8 dB.

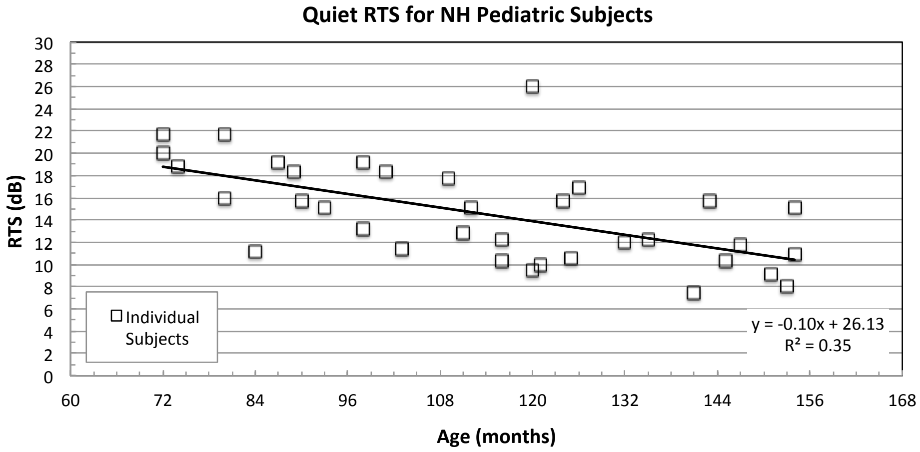


Figure 6. RTS obtained in quiet for all NH pediatric subjects
RTS (dB) obtained in quiet are plotted as a function of age (in months) for normal-hearing pediatric subjects. The regression line represents a simple linear fit of the individual data. *Note lower numbers indicate better performance.

Average data across years of age are shown in Figure 7 (see Appendices R and O) for NH pediatric subjects in addition to those of NH adult subjects. In this iteration, subjects were binned into age groups (6;0-6;11, 7;0-7;11, 8;0-8;11, 9;0-9;11, 10;0-10;11, 11;0-11;11, 12;0-12;11), designated by years, to make later comparisons across conditions simpler. A simple linear fit of the mean data was calculated, as was performed on the individual data (see Fig. 6). Although the slopes between the two figures appear to be different at first glance, it should be noted that the x-axes differ between Figs. 6 and 7 by a factor of 12; individual data are displayed as a function of months (Fig. 6), whereas average data are displayed as a function of years (Fig. 7). When the slope of the fitted line based on the individual data is multiplied by 12, a very similar slope is obtained to that of the fitted line based on the average data. Adult-like performance appears to have been achieved by 11 years in this quiet condition. The differences between the 11- and 12-year old mean scores compared to the adult mean score was less than 1 dB (considered to be essentially adult-like if the difference was less than 1 dB). Developmental improvements in this quiet condition may be partially explained by the nearly 5 dB improvement seen in measured hearing thresholds (pure-tone average) as children aged from six to 12 years of age (see Appendix W).

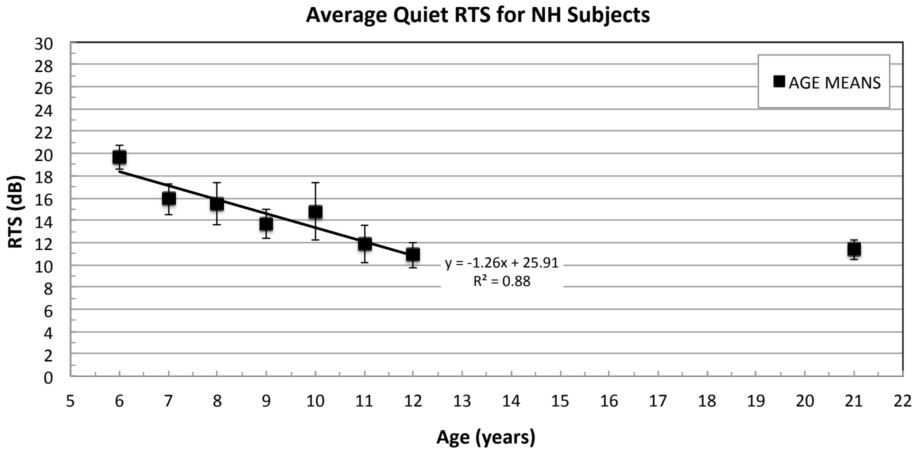


Figure 7. Average RTS obtained in quiet for NH subjects
RTS (dB) obtained in quiet are plotted as a function of age (in years) for normal-hearing subjects. Filled square symbols indicate the average RTS per age group (mean data point for adults is shown at the group's mean age of 21). The error bars denote ±1 standard error of the mean. The regression line represents a simple linear fit of the average data points. *Note lower numbers indicate better performance.

3.4.1.2 UHL Subjects

Reception thresholds for sentences were measured in quiet for children with UHL and are shown in Fig. 8 along with dashed lines showing ± 1 standard deviation from the NH age means estimated from the fitted equation (see Appendix U for all data). As detailed in the Methods section, the square root of the average variance across ages was taken as the standard deviation. The equation from the fitted line (based on the average values) in Fig. 7 was used to predict the means and the ±1 standard deviation for NH pediatric subjects. Each UHL subject's age is marked with a resolution of years and months. All unaided UHL subjects (_U) and one aided subject (11_CROS) fell above one standard deviation of the NH means, indicating poorer performance than NH subjects. It should be noted that all UHL subjects had NH in the unimpaired ear (250-8000 Hz) with the exception of subject (9_U) who had mild hearing loss at 1000 and 3000 Hz only. Additionally, all subjects had excellent (≥ 90% correct) word recognition performance in their unimpaired ear. Intriguingly, only the two subjects who wore a hearing aid fell within the ± 1 standard deviation boundaries. It is of interest to note the subject who participated in the experiment twice showed improved performance in the quiet condition when using her hearing aid (9_HA2*) compared to her initial score unaided (8_U*). Results suggest that subjects aided with a traditional hearing aid may be benefiting from binaural summation, a binaural process that was unavailable to the subject wearing a CROS system and all unaided subjects. These findings hint at decrements when listening in quiet environments (the easiest of listening condition tested) for UHL subjects who do not use a conventional hearing aid.

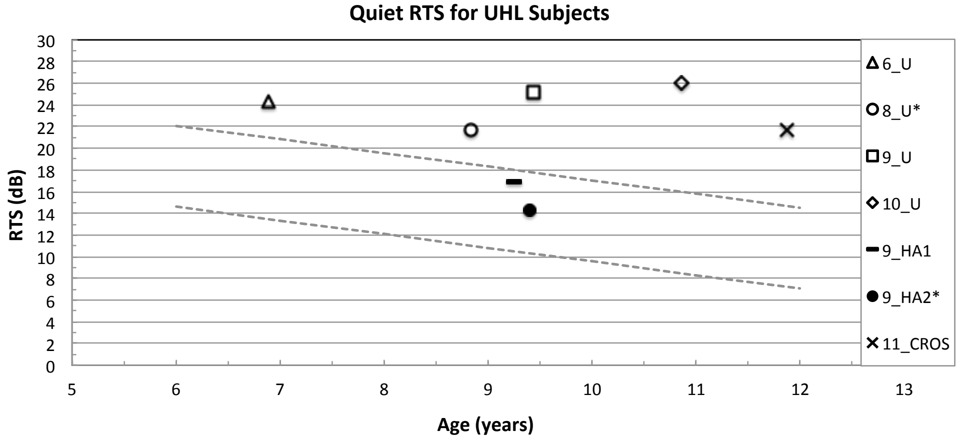


Figure 8. RTS obtained in quiet for all UHL subjects
RTS (dB) obtained in quiet are plotted as a function of age (in years) for subjects with UHL. Each subject with UHL is denoted by a unique symbol. Note: 8_U* and 9_HA2* represent the same subject who participated twice in the experiment. Dashed lines represent ± 1 standard deviation from the normal-hearing age means. Note: lower numbers indicate better performance.

3.4.2 Conditions Employing Co-located Maskers

Reception thresholds for sentences were measured in the presence of two co-located masker types (SSN and TTB). Both target and masking signals were presented from the same loudspeaker positioned at 0° (Front/Front).

3.4.2.1 NH Subjects

Reception thresholds for sentences for NH pediatric subjects are shown below in Fig. 9a (SSN) and 9b (TTB) (see Appendix Q for individual subject data). Performance across the two maskers was compared using a paired sample t-test. A significant effect of masker type was found, $t(34) = -10.3$, $p < .001$. Two-talker babble proved to be a less effective masker than SSN for pediatric subjects, suggesting children demonstrated fluctuating masker benefit. Pearson product-moment correlation coefficients were computed to assess the relationship between age and RTS in co-located SSN and TTB. Strong, negative correlations between RTS performance and age were found for both SSN, $r(33) = -0.51$, $p < 0.001$ and TTB, $r(33) = -0.75$, $p < .001$, suggesting performance in the presence of masking sounds improves (i.e., RTS decreases) as children get older.

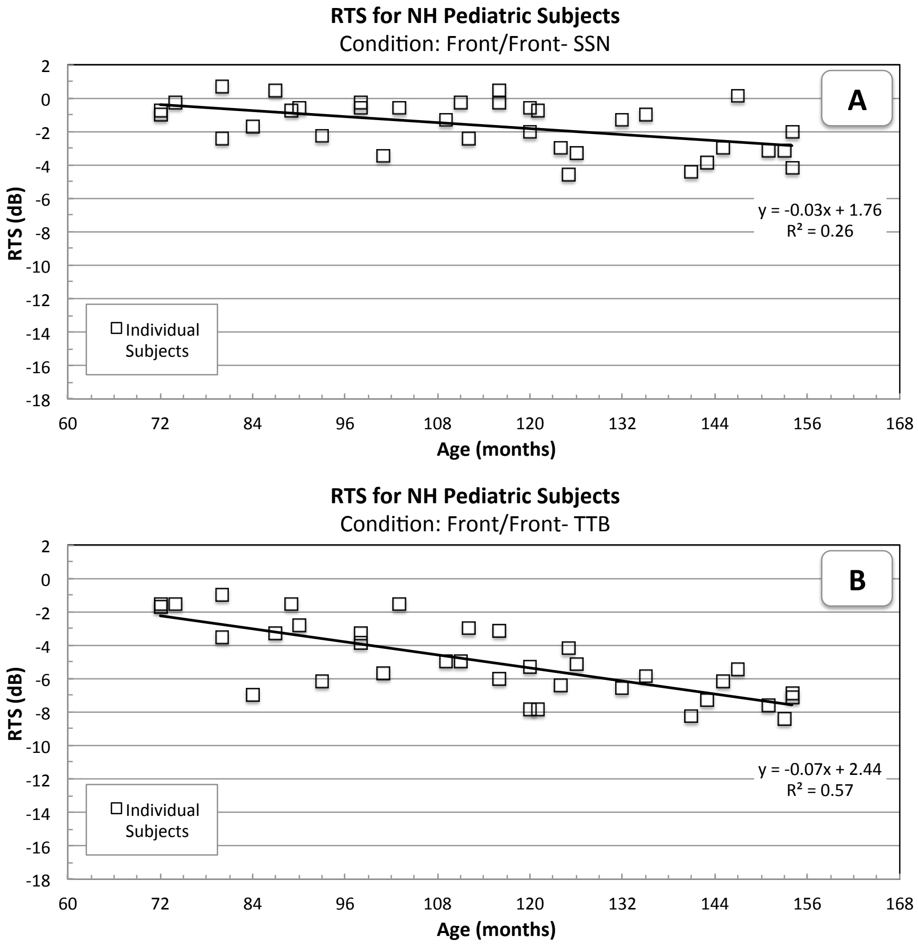


Figure 9. RTS in the presence of a co-located SSN masker (a) and a TTB masker (b) for NH pediatric subjects.

RTS in the presence of a co-located SSN masker (Fig. 9a) and TTB masker (Fig. 9b) are plotted as a function of age (in months) for NH pediatric subjects. The regression line represents a simple linear fit of the individual data. *Note lower numbers indicate better performance.

The data are repotted below in Fig. 10 after grouping subjects by year of age. Slopes are now in dB/year and agree with those in dB/month (in Fig. 9) when multiplied by 12. As age increased from five to 12 years, performance improved for both masker types, but to a greater degree for TTB (slope = -0.83 dB/year) versus SSN (slope = -0.35 dB/year), see Fig. 10. Adult-like performance appears to be achieved by 10 years for SSN (0.75 dB difference between the 10-year-old and 21-year-old means), but is still not achieved by 12 years of age for TTB (2.27 dB difference between the 12-year-old and 21-year-old means), likely pointing to continued maturation of perceptual processing.

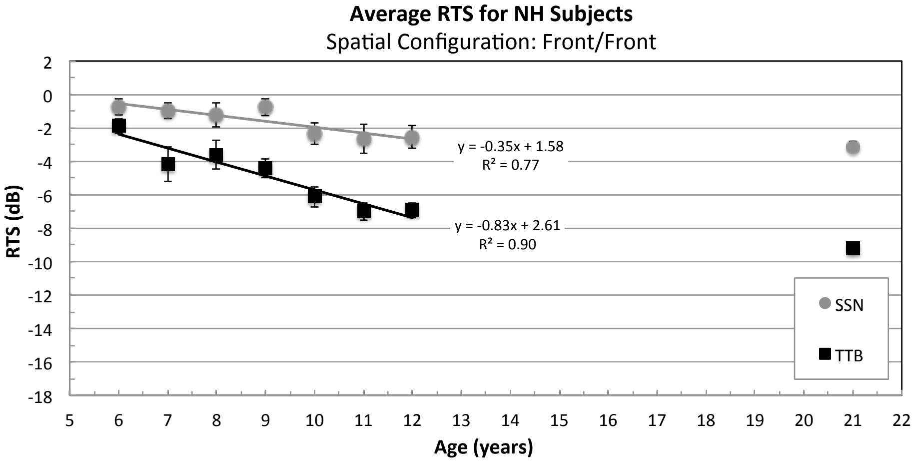


Figure 10. Average RTS in the presence of co-located SSN and TTB maskers for NH subjects.

Average RTS (dB) in the presence of a co-located SSN masker (grey circles) and TTB masker (black squares) are plotted as a function of age (in years) for NH subjects. Mean data point for adults is shown at the group's mean age of 21. The error bars denote ±1 standard error of the mean. The regression line represents a simple linear fit of the mean data points. Note: lower numbers indicate better performance.

3.4.2.2 UHL Subjects

Reception thresholds for sentences for UHL subjects are shown in Fig. 11a (SSN) and 11b (TTB) along with dashed lines showing ±1 standard deviation from the NH age means estimated from the fitted equations (see Appendix U for all data). As detailed in the Methods section, the square root of the average variance across ages was taken as the standard deviation. The equations from the fitted lines (based on the average values) in Fig. 10 were used to predict the means and the ±1 standard deviation for NH pediatric subjects. Each UHL subject's age is marked with a resolution of years and months. For SSN, there is little difference observed between subjects with UHL and age-matched, NH control subjects. Performance of subjects with UHL largely fell on or within ± 1 standard deviation of the NH mean. With TTB, however, there was a greater difference observed between subjects with UHL and age-matched, NH control subjects. For all but two subjects with UHL, performance fell above one standard deviation of the NH means, indicating poorer performance than most NH subjects. Findings suggest that even when no spatial cues are present (i.e., co-located speech and masker signals), performance differences are found between children with NH and UHL with the two-talker child babble. The children with UHL required a more advantageous SNR to achieve similar performance in the presence of two competing talkers as their normal-hearing counterparts.

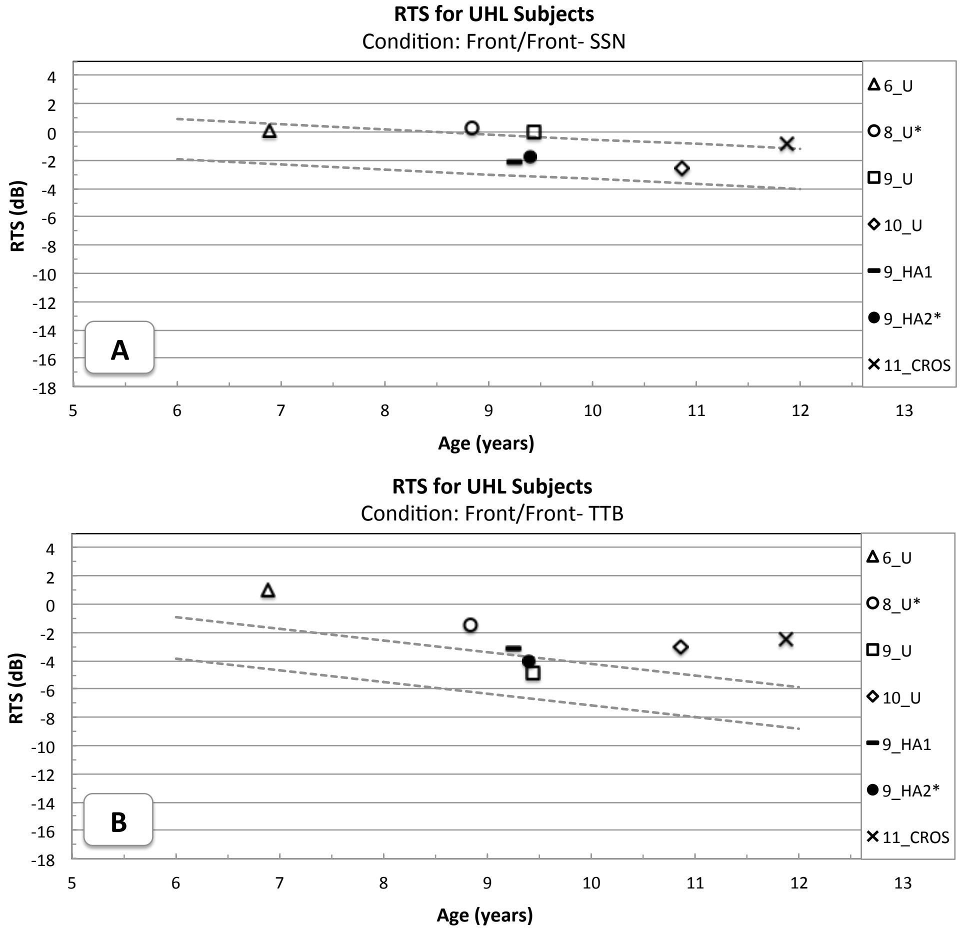


Figure 11. RTS in the presence of a co-located SSN masker (a) and TTB masker (b) for all UHL subjects.

RTS (dB) in the presence of a co-located SSN masker (Fig. 11a) and TTB masker (Fig. 11b) are plotted as a function of age (in years) for UHL subjects. Each subject with UHL is denoted by a unique symbol. Note: 8_U* and 9_HA2* represent the same subject who participated twice in the experiment. Dashed lines represent ± 1 standard deviation from the normal-hearing age means.

3.4.3 Conditions Employing Spatially Separated Maskers

Reception thresholds for sentences were measured in the presence of two spatially separated masker types (SSN and TTB). The target signal was always presented from the front loudspeaker located at 0°. The masking signals were presented in either asymmetrical (masking signals presented from only one side speaker at +60° or -60°) or symmetrical (±60°) masking signals presented from both side speakers configurations.

3.4.3.1 Asymmetrical Masking Configuration

3.4.3.1.1 NH Subjects

Average reception thresholds for sentences for NH subjects are shown below in Fig. 12a (SSN) and 12b (TTB) in the asymmetrical masking configurations (see Appendices R and O for mean data). Both asymmetrical configurations are plotted within each figure. Circle symbols represent conditions when the masker was presented from the right side speaker at +60° and square symbols represent conditions when the masker was presented from the left side speaker at -60°. A paired sample t-test revealed a significant difference of masker location (+60° versus -60°) for NH pediatric subjects with SSN, $t(34) = 3.67$, $p < 0.001$, but not with TTB, $t(34) = 0.92$, $p = 0.36$. For SSN, it appears that NH subjects had a small but significant improvement in performance when the masker was directed toward their left ear, indicating a possible right ear advantage in this condition. No significant difference was observed with TTB, which is likely be due to increased variance in this condition.

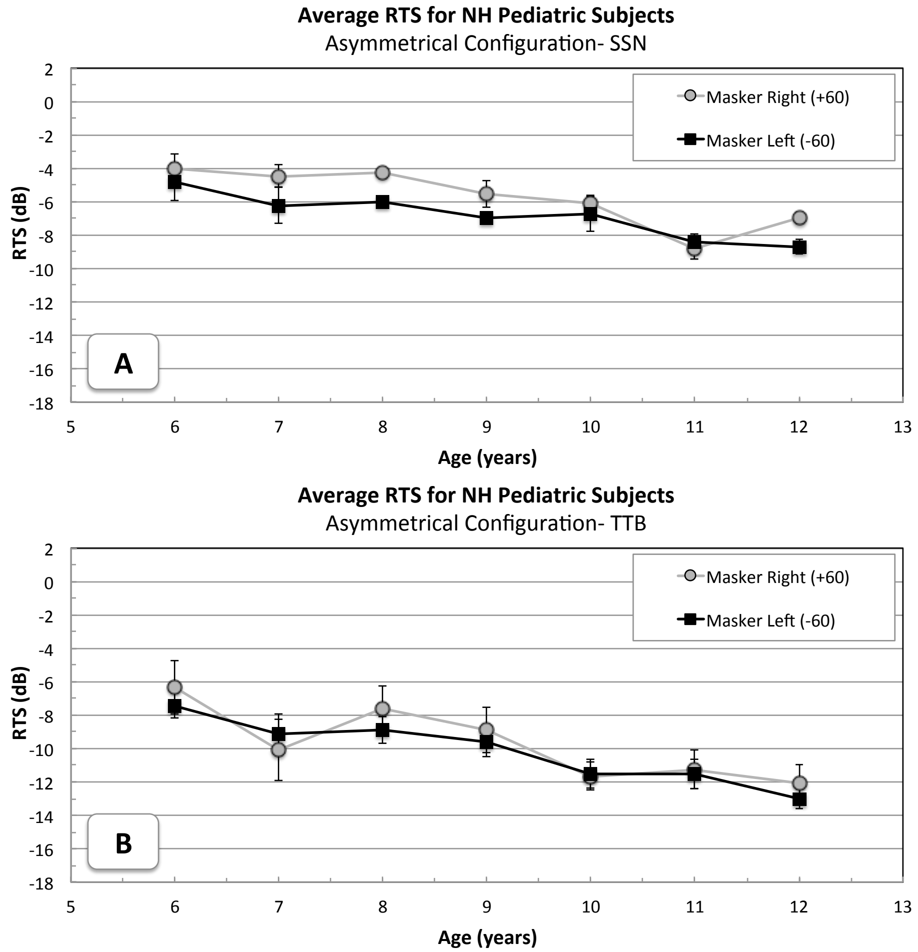


Figure 12. Average RTS in the presence of an asymmetrically placed SSN masker (a) and TTB masker (b) for NH pediatric subjects.
Average RTS (dB) in the presence of an asymmetric interfering masker are plotted as a function of age (in years) for NH pediatric subjects. RTS in the presence of SSN are plotted in Fig. 12a and in the presence of TTB in Fig. 12b. Black square squares = masker presented from loudspeaker positioned at -60°; grey circles symbols = masker presented from loudspeaker positioned at +60°. The error bars denote ±1 standard error of the mean.

For ease of interpretation, performance of conditions Front/Right (0°/+60°) and Front/Left (0°/-60°) was averaged across the two conditions and is subsequently discussed as Front/Side. Therefore each individual data point plotted below is the average of four RTS (two from condition Front/Right and two from condition Front/Left). These averaged RTS for NH subjects are shown below in Figs.

13a (SSN) and 13b (TTB) (see Appendix Q for individual subject data). Performance across the two maskers was compared in NH pediatric subjects using a paired sample t-test. A significant effect of masker type was found, $t(34) = -13.19$, $p < 0.001$. Two-talker babble proved to be a less effective masker than SSN for pediatric subjects. Pearson product-moment correlation coefficients were computed to assess the relationship between age and RTS for SSN and TTB. Strong, negative correlations between RTS and age were found between age and RTS performance for SSN, $r(33) = -0.71$, $p < 0.001$ and TTB, $r(33) = -0.67$, $p < 0.001$.

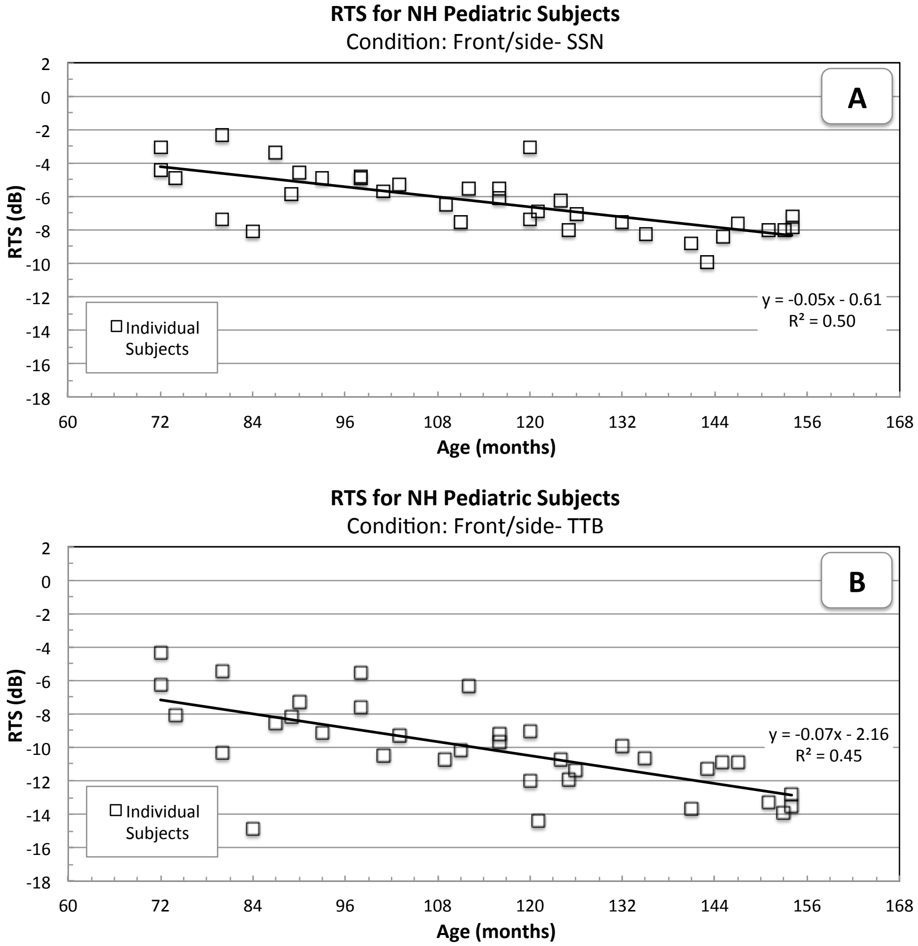


Figure 13. RTS in the presence of asymmetrically placed SSN masker (a) and TTB masker (b) for NH pediatric subjects.
RTS (dB) in the presence of an asymmetric interfering masker are plotted as a function of age (in months) for NH pediatric subjects. RTS in the presence of SSN are plotted in Fig. 13a and in the presence of two-talker babble in Fig. 13b. The error bars denote ±1 standard error of the mean. The regression line represents a simple linear fit of the individual data.

The data are repotted below in Fig. 14 after grouping subjects by year of age. Slopes are now in dB/year and agree with those in dB/month (in Fig. 13) when multiplied by 12. As age increased from five to 12 years, performance improved for both masker types, but to a greater degree for TTB (slope = -0.85 dB/year) than SSN (slope = -0.65 dB/year), see Fig. 16 below. Adult-like performance appears to be well formed by age 11 years for SSN (difference of 0.17 dB between the average 11- and 21-year-old performance), but not yet achieved by age 12 years for TTB (difference of 1.83 dB between the average 12- and 21-year-old performance).

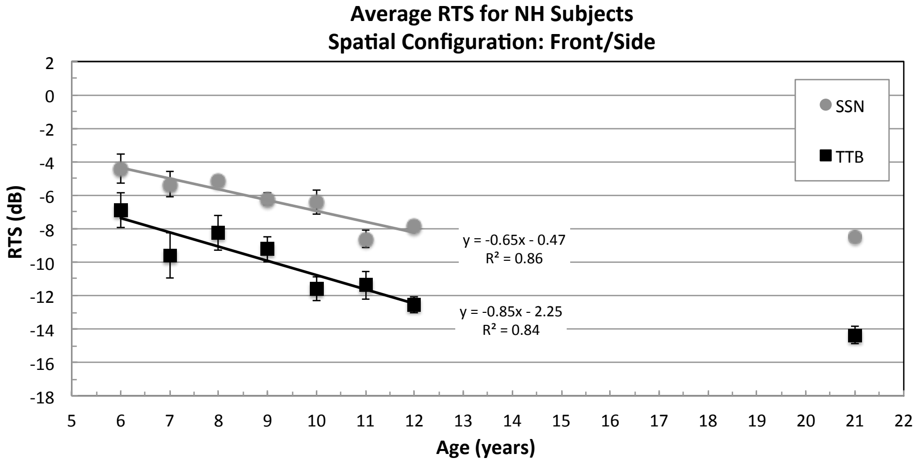


Figure 14. Average RTS in the presence of an asymmetrically placed SSN and TTB maskers for NH subjects.
Average RTS (dB) in the presence of asymmetric SSN (grey circles) and TTB (black squares) masker are plotted as a function of age (in years) for NH subjects. Mean data point for adults is shown at the group's mean age of 21. The error bars denote ±1 standard error of the mean. The regression line represents a simple linear fit of the mean data points.

Spatial release from masking (SRM) was calculated by comparing performance in the co-located versus spatially separated conditions for each masker type. Reception thresholds for sentences obtained in condition Front/Front (co-located target and masker signals) were subtracted from those obtained in condition Front/Side (target from the front speaker and masker signals from side speaker). This yielded the amount of improvement, known as spatial release from masking (expressed in dB), realized by moving the masking signal from the same speaker location as the target to a side speaker positioned at either +60° or -60°. Spatial release from masking is shown below in Figs. 15a (SSN) and 15b (TTB). See

Appendices S and T for individual subject and mean data, respectively. A paired sample t-test was performed to compare SRM across SSN and TTB. No significant difference was found, $t(34) = -0.42$, $p = 0.68$. Pearson product-moment correlation coefficients were computed to assess the relationship between age and SRM for SSN and TTB. A moderate, positive correlation between SRM and age was found for SSN, $r(33) = 0.354$, $p = 0.04$. No significant correlation between SRM and age was found for TTB, $r(33) = 0.74$, $p = 0.67$.

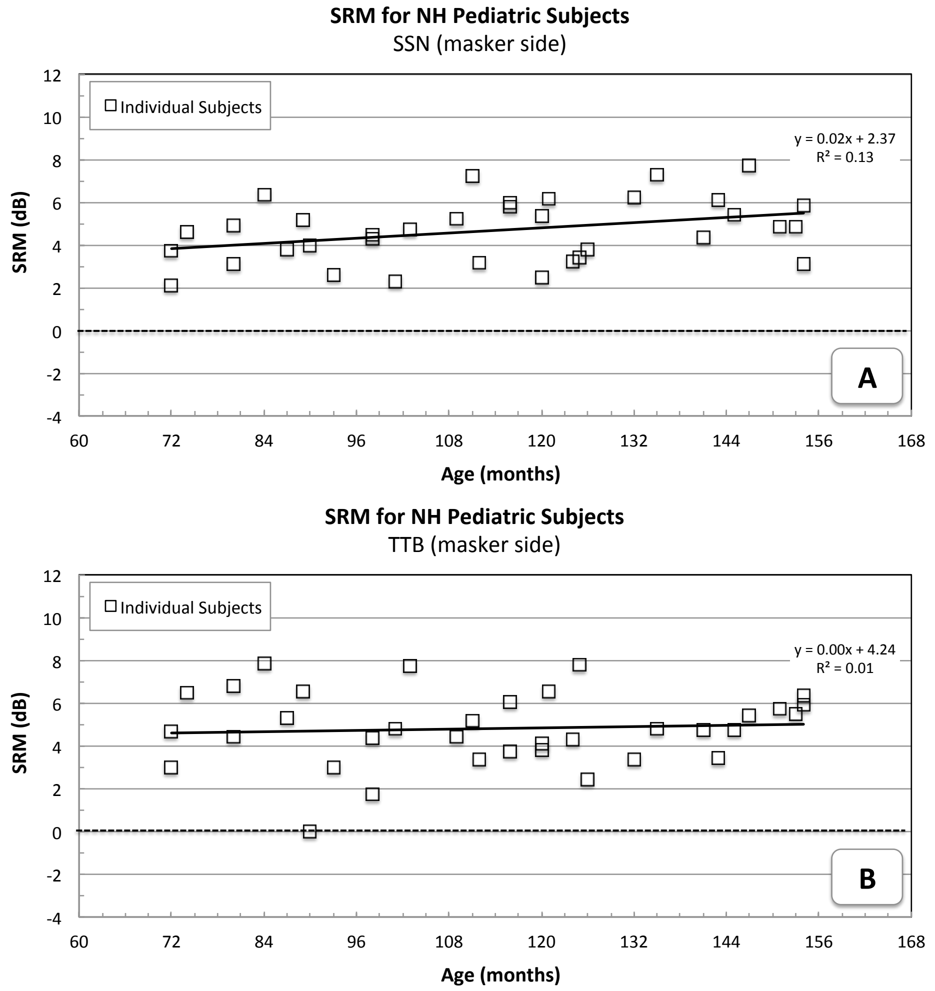


Figure 15. SRM for asymmetrically placed SSN masker (a) and TTB masker (b) for NH pediatric subjects.

SRM (dB) is plotted as a function of age (in months) for NH pediatric subjects. SRM with SSN is plotted in Fig. 15a and with two-talker babble in Fig. 15b. The regression line represents a simple linear fit of the individual data. The dotted line at zero indicates no SRM. *Note higher numbers indicate more benefit.

The data are repotted below in Fig. 16 after grouping subjects by year of age. Slopes are now in dB/year and agree with those in dB/month (in Fig. 15) when multiplied by 12. For TTB, it appears that the amount of SRM is fairly consistent across age (~5 dB, see Fig. 16). These results indicate that children as young as six years old are able to benefit from spatially separating the target and TTB in an asymmetrical configuration to the same extent as a 12- or 21-year old. This effect was not as constant with SSN (see Fig. 16) where it appears that the amount of SRM increased slightly with age (difference of 1.68 dB between six- and 21-year-old average performance) and became adult-like by 11 years of age (difference of 0.7 dB between 11- and 21-year-old average performance).

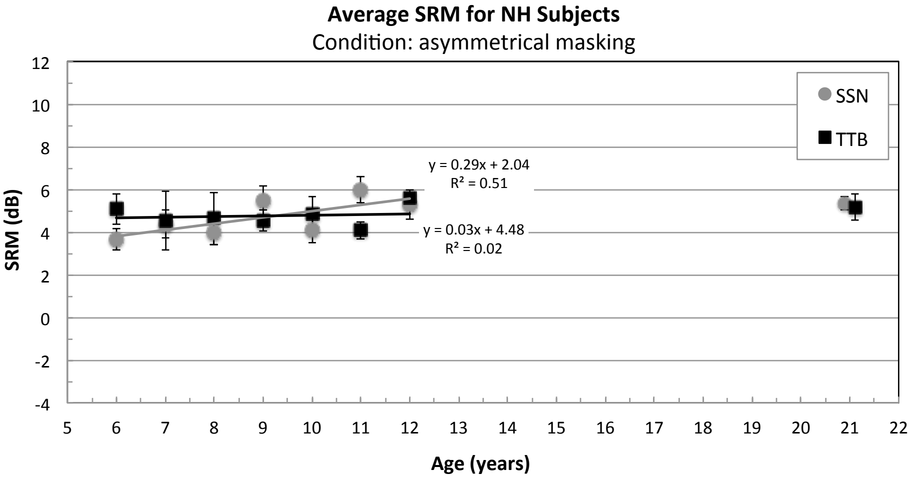


Figure 16. Average SRM for asymmetrically placed SSN and TTB maskers for NH subjects.

SRM (dB) is plotted as a function of age (in years) for NH subjects for SSN (grey circles) and TTB (black squares). Mean data point for adults is shown at the group's mean age of 21. The error bars denote ±1 standard error of the mean. The regression line represents a simple linear fit of the mean data. The dotted line at zero indicates no SRM. Note: higher numbers indicate more benefit.

3.4.3.1.2 UHL subjects

To even a greater extent than for listeners with NH, moving the masker to ±60° affected the performance of subjects with UHL. All performance results are separated into spatial configurations referred to as either Front/Impaired (masker directed towards the subject's impaired ear) or Front/Normal (masker directed towards the subject's normal-hearing ear). Reception thresholds for sentences for

SSN and TTB are displayed below in Fig. 17 along with dashed lines showing ± 1 standard deviation from the NH age means estimated from the fitted equations (see Appendix U for all data). As detailed in the Methods section, the square root of the average variance across ages was taken as the standard deviation. The equations from the fitted lines (based on the average values) in Fig. 14 were used to predict the means and the ±1 standard deviation for NH pediatric subjects. Each UHL subject's age is marked with a resolution of years and months.

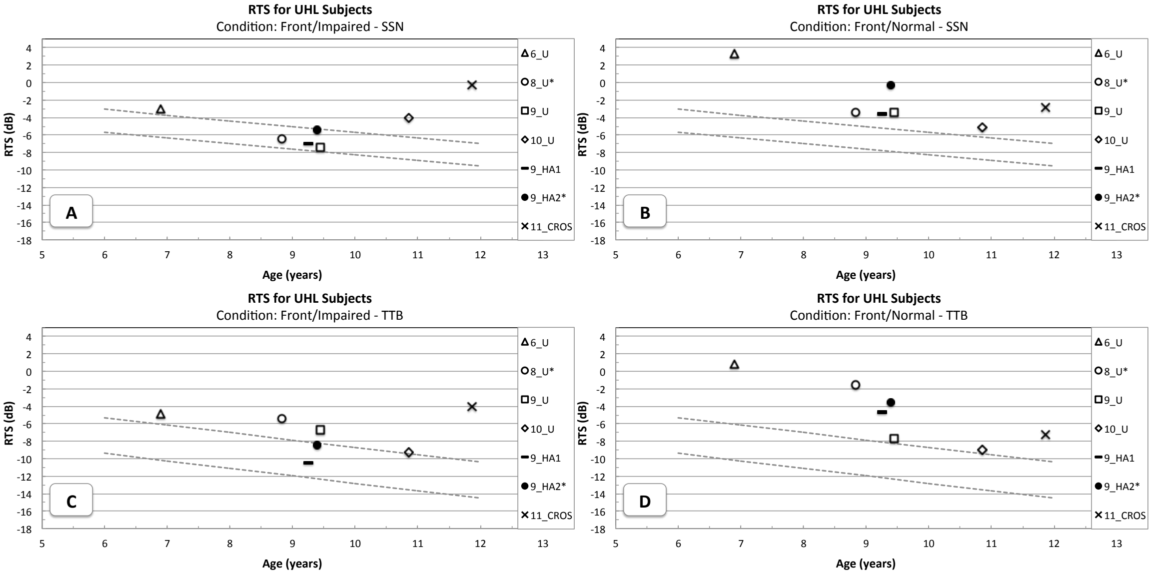


Figure 17. RTS for UHL subjects in masking configurations Front/Impaired and Front/Normal and for masker types SSN and TTB.
RTS (dB) in the presence of an interfering masker are plotted as a function of age (in years) for subjects with UHL. Figs. 17a and 17b display performance with masker type SSN, while Figs. 17c and 17d display performance with masker type TTB. Figs. 17a and 17C display performance in spatial configuration Front/Impaired, while Figs. 17b and 17d display performance in spatial configuration Front/Normal. Each subject with UHL is denoted by a unique symbol. Note: 8_U* and 9_HA2* represent the same subject who participated twice in the experiment. Dashed lines represent ± 1 standard deviation from the NH age means.

First, a large difference is noted between performance across spatial conditions Front/Impaired (Figs. 17a and c) and Front/Normal (Figs. 17b and d). In spatial configuration, Front/Normal for both SSN and TTB, all subjects with UHL fell above one standard deviation of the NH mean, indicating poorer performance than most NH subjects. In spatial configuration, Front/Impaired, performance results were mixed. With SSN (Fig. 17a), many subjects (four out of seven) with UHL performed within the ± 1 standard deviation boundaries, indicating similar performance to age-matched, NH subjects. With TTB (displayed in Fig. 17c), only two subjects fell within the ± 1 standard deviation boundaries, while the others fell above one standard deviation of the NH mean. Although the effect of age is challenging to assess with only seven UHL subjects; it appears there may be some developmental trends emerging. Performance appears to improve with increasing age and is most apparent for spatial condition Front/Normal.

Spatial release from masking was calculated, as previously described, to compare performance in the co-located versus spatially separated conditions for each masker type. Spatial release from masking is displayed in Fig. 18 for all listening conditions along with dashed lines showing ± 1 standard deviation from the predicted NH age means in the averaged spatial configuration Front/Side (see Appendix V for all data). When the masker was directed to subjects' NH ears (displayed in Figs 18b and d), a majority of subjects fell below one standard deviation of the NH mean, indicating less SRM than most NH subjects. Additionally, for several UHL subjects no SRM benefit was observed. When the masker was directed towards subjects' impaired ear (Figs. 18a and c) results were mixed. For some subjects SRM benefit fell within ± 1 standard deviation of the NH mean (most notably for TTB), while others fell either above or below one standard deviation of the NH mean. For three subjects (8_U*, 9_U, 9_HA1) SRM fell above one standard deviation of the NH mean, indicating a small advantage in the Front/Impaired listening condition compared to most NH subjects (see Fig. 18a). Additionally, no clear developmental age effect was observed. It appears that the amount of SRM was fairly constant across age for subjects with UHL, as was the case for NH subjects.

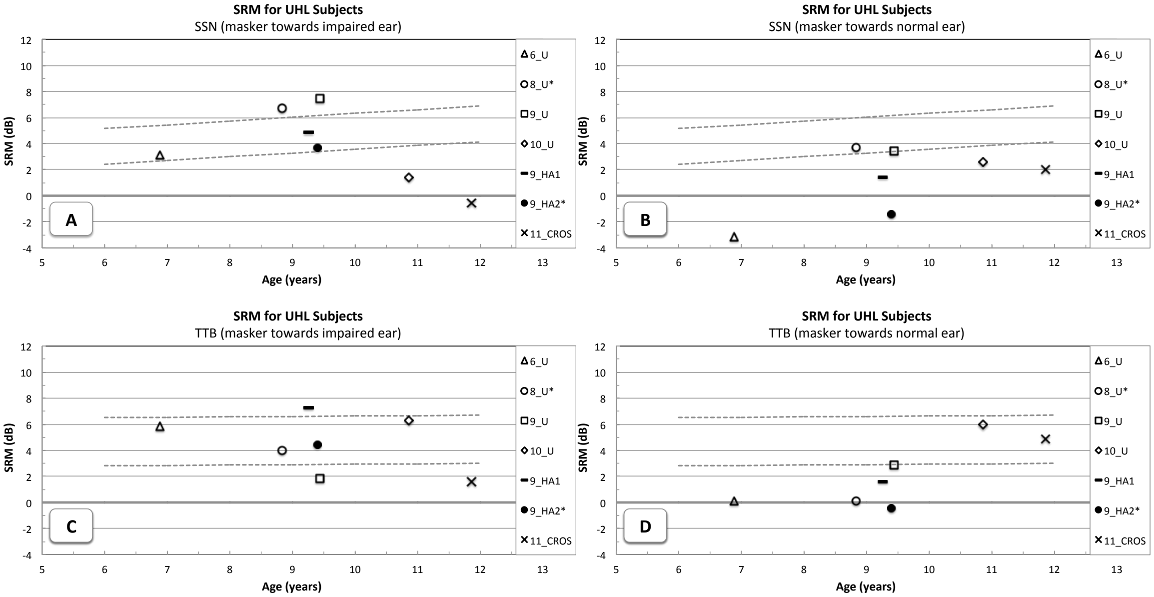


Figure 18. SRM for UHL subjects when the masker was directed towards the impaired ear or the normal ear and for masker types SSN and TTB.
SRM (dB) is plotted as a function of age for subjects with UHL. Figs. 18a and 18b display SRM for masker type SSN, while Figs. 18c and 18d display SRM for masker type TTB. Figs. 18a and 18C display SRM when the masker was directed towards the impaired ear, while Figs. 18b and 18d display SRM when the masker was directed towards the normal ear. Each subject with UHL is denoted by a unique symbol. Note: 8_U* and 9_HA2* represent the same subject who participated twice in the experiment. Dashed lines represent ± 1 standard deviation from the NH age means. The grey solid line at zero indicates no SRM benefit. Higher numbers indicate more benefit.

To better understand the effect of spatial configuration and masker type on SRM within subjects with UHL an additional set of figures is presented below, which re-plots the data from Fig. 18. The effect of spatial configuration on SRM is displayed for each masker type across subjects in Fig. 19a (Front/Impaired) and Fig. 19b (Front/Normal). In the asymmetrical masking condition Front/Impaired (Fig. 19a) four of seven subjects with UHL demonstrated more SRM benefit with TTB than with SSN. Only two subjects clearly demonstrated more SRM benefit with TTB than with SSN in condition Front/Normal (Fig. 19 b). Additionally, for nearly all subjects for both masker types, more SRM benefit was observed in spatial configuration Front/Impaired than Front/Normal. The exception to this observation was for the 11-year-old child using a CROS hearing system. For this subject, more SRM benefit was noted in condition Front/Normal versus Front/Impaired. Furthermore, a decrement in performance (0.6 dB) was noted for this subject when listening to SSN in spatial configuration Front/Impaired, the only instance of decreased performance in this spatial configuration among UHL subjects.

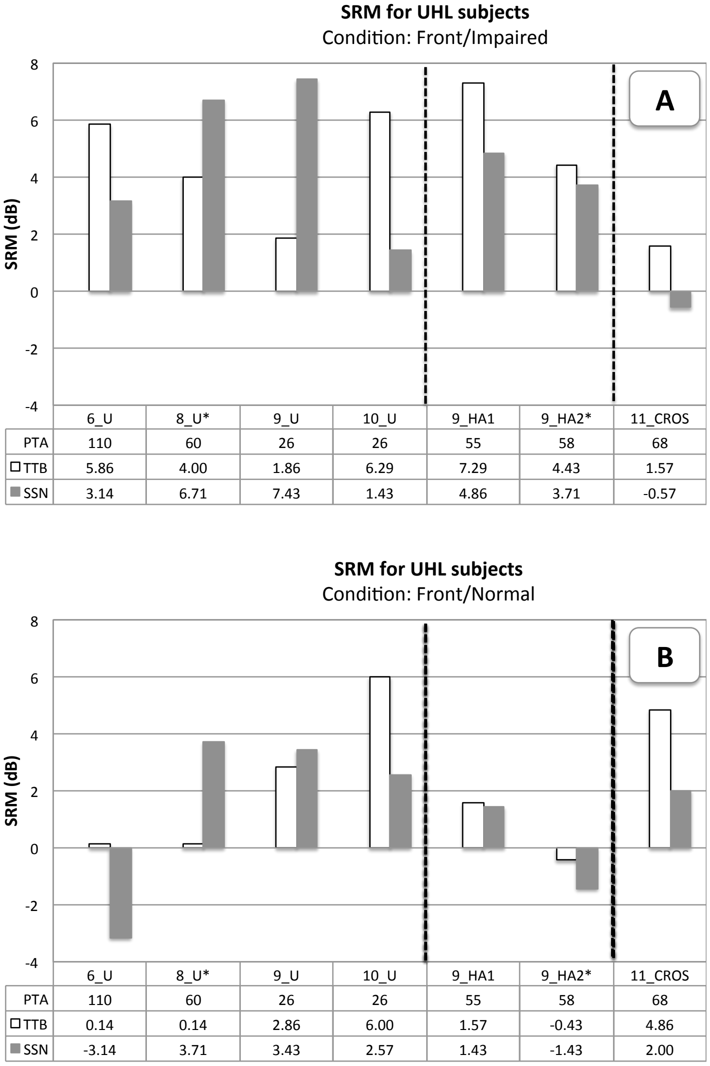


Figure 19. SRM for UHL subjects in masking configurations Front/Impaired and Front/Normal for each masker type.

SRM benefit (dB) for all UHL subjects is displayed for both masker types and spatial configurations Front/Impaired (Fig. 19a) and Front/Normal (Fig. 19b). Unfilled bars represent SRM when listening in the presence of the TTB. Grey filled bars represent SRM when listening in the presence of SSN. For reference, the PTA is also provided for each subject. Vertical dashed lines separate subjects into three groups: 1) unaided (_U), 2) aided with traditional hearing aid (_HA), 3) aided with CROS hearing aid system (_CROS).

In summary, most subjects with UHL were able to benefit from spatially separating SSN and TTB maskers from the target signal (i.e., moving it to the left or right) in most of the listening conditions. The amount of SRM benefit depended on the individual child, masker type, and spatial configuration. In spatial configuration Front/Impaired (meaning the masker was directed to the ear with hearing loss), many subjects with UHL received similar amounts of benefit when compared to age-matched NH control subjects (especially evident for TTB). Conversely in spatial configuration Front/Normal, most subjects with UHL demonstrated less SRM benefit than age-matched NH control subjects. With a few exceptions, subjects with UHL demonstrated more SRM benefit with masker type TTB relative to SSN in spatial configuration Front/Impaired.

3.4.3.2 Symmetrical Masking Configuration

3.4.3.2.1 NH subjects

Reception thresholds for sentences in the symmetrical masking configuration (i.e., maskers at both ±60° locations) for NH pediatric subjects are shown below in Fig. 20 (see Appendix Q for individual subject data). Only the real speech masker (TTB) was tested in the symmetrical masking configuration with the speech from one of each of the talkers coming from a different loudspeaker. A Pearson product-moment correlation coefficient was computed to assess the relationship between age and RTS. A moderate, negative correlation was found, $r(33) = -0.36$, $p = .02$). As age increased from five to 12 years, performance improved (RTS decreased). Adult-like performance in this condition was still not fully achieved for the 12-year-old group (2.6 dB difference between the predicted 12 and mean 21-year old performance), see Fig. 21 for presentation of data binned by years of age.

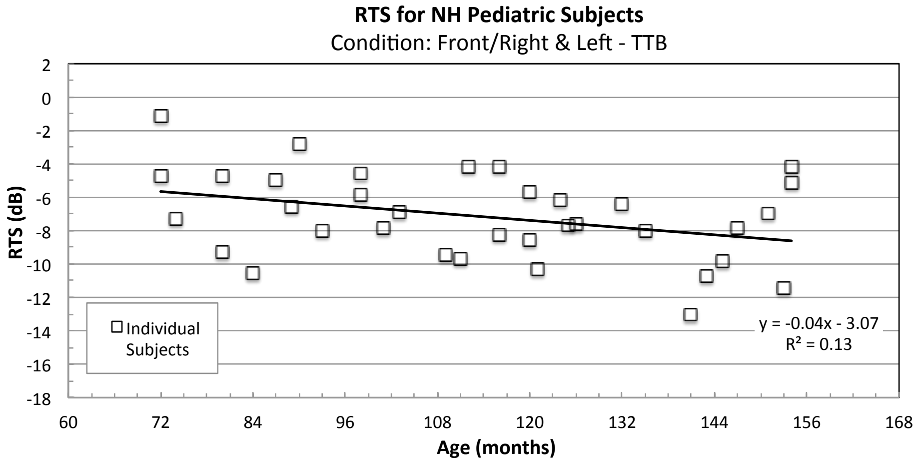


Figure 20. RTS in the presence of a symmetrically placed TTB masker for NH pediatric subjects.

RTS (dB) in the presence of a symmetrical TTB masker are plotted as a function of age (in months) for NH pediatric subjects. The regression line represents a simple linear fit of the individual data. *Note lower numbers indicate better performance.

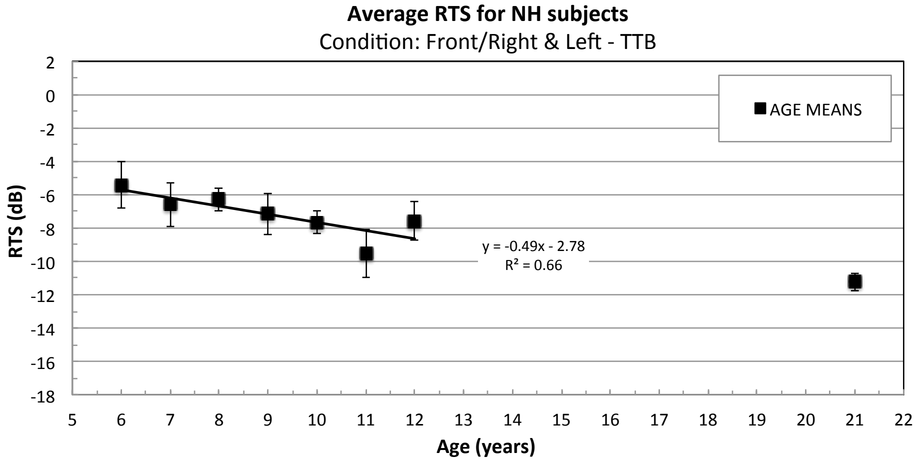


Figure 21. Average RTS in the presence of a symmetrically placed TTB masker for NH subjects.

Average RTS (dB) in the presence of a symmetrical TTB masker are plotted as a function of age (in years) for normal-hearing subjects (mean data point for adults is shown at the group's mean age of 21). The error bars denote ±1 standard error of the mean. The regression line represents a simple linear fit of the mean data points. *Note lower numbers indicate better performance.

Average performance in the asymmetric and symmetric masking configurations was compared across all NH subjects and is displayed in Fig. 22. Using a paired sample t-test a significant effect of spatial configuration was found, $t(34) = -7.89$, $p < 0.001$, with better performance in the asymmetrical configuration. The average difference was approximately 3 dB when collapsed across all age groups and may be explained by a lack of a consistent better ear advantage in the symmetrical condition.

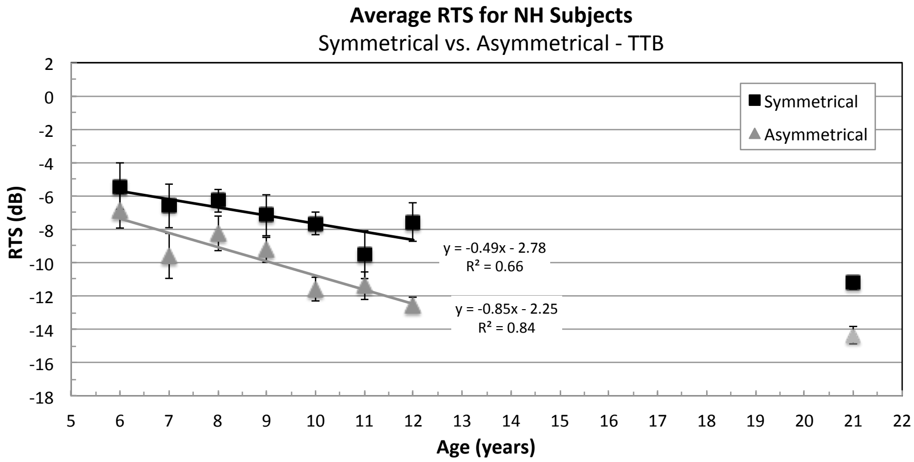


Figure 22. Average RTS in asymmetrical and symmetrical masking conditions with the TTB masker for NH subjects.

Average RTS (dB) in the presence of TTB are plotted as a function of age (in years) for NH subjects. Black filled square symbols represent performance in the symmetrical masking configuration. Grey filled triangles represent performance in the asymmetrical masking configuration. The error bars denote ±1 standard error of the mean.

Spatial release from masking was calculated, as previously described, to compare performance in the co-located versus this symmetrical spatially separated condition. Spatial release from masking (SRM) benefit is shown below in Figs. 23 (individual data) and 24 (average data) (see Appendices S and T for individual and mean data). A Pearson product-moment correlation coefficient was computed to assess the relationship between age and SRM. A moderate, negative correlation was found between age and SRM, *r*(33) = -0.35, p = .04. As age increased from six to 12 years, the amount of SRM decreased, unlike the pattern of results observed in asymmetric masking paradigms. Adult-like SRM appears to have been achieved early on, by seven years of age (difference of 0.4 dB between seven- and 21-year old average SRM).

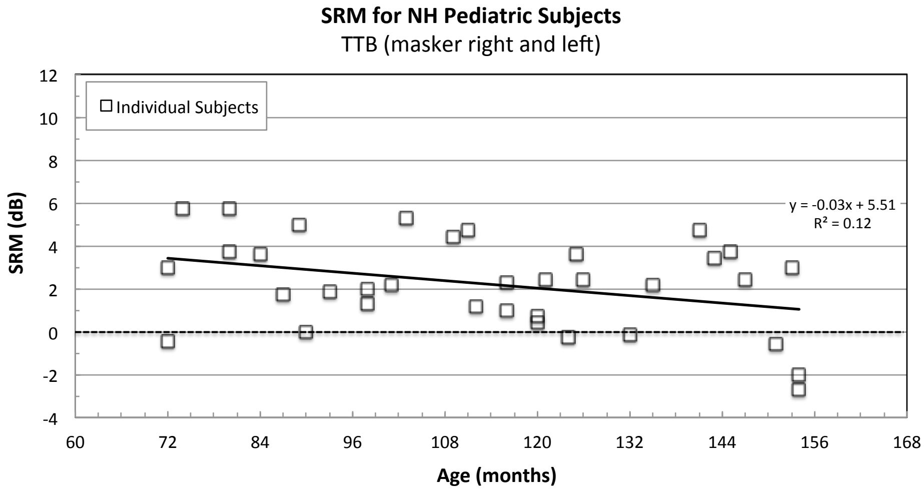


Figure 23. SRM for a symmetrically placed TTB masker for NH pediatric subjects.

SRM (dB) is plotted as a function of age (in months) for NH pediatric subjects. The regression line represents a simple linear fit of the individual data points. *Note higher numbers indicate more benefit.

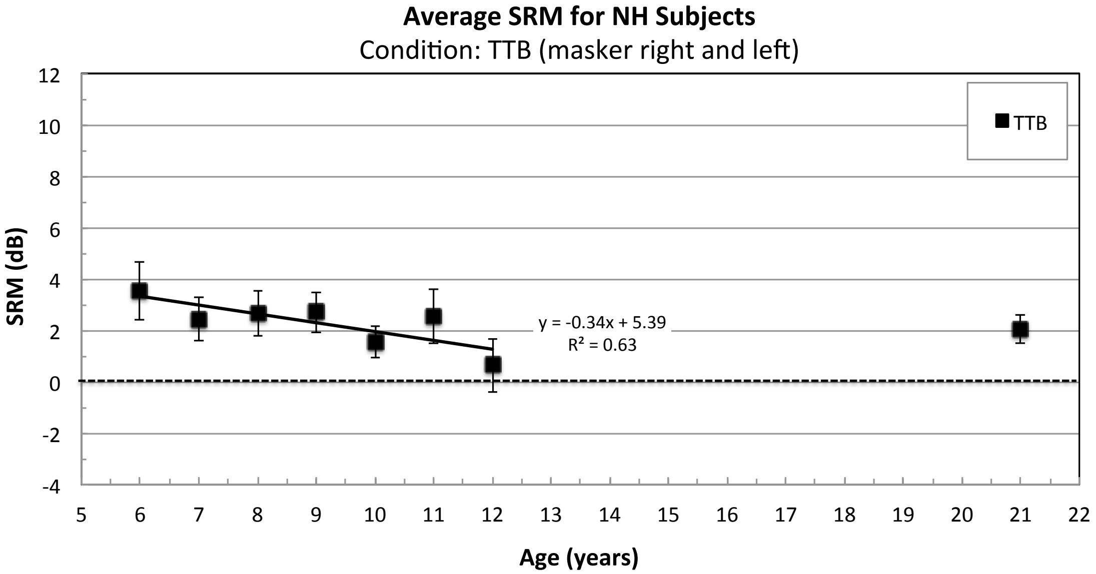


Figure 24. Average SRM for a symmetrically placed TTB masker for NH subjects.

Average SRM (dB) is plotted as a function of age (in years) for NH subjects (mean data point for adults is shown at the group's mean age of 21). The error bars denote ±1 standard error of the mean. The regression line represents a simple linear fit of the mean data. *Note higher numbers indicate more benefit.

3.4.3.2.2 UHL subjects

Reception thresholds for sentences for UHL subjects in the symmetrical masking condition are shown below in Fig. 25 along with dashed lines showing ± standard deviation from the NH age means estimated from the fitted equation. As detailed in the Methods section, the square root of the average variance across ages was taken as the standard deviation. The equation from the fitted line (based on the average values) in Fig. 21 was used to predict the means and the ± 1 standard deviation for NH pediatric subjects. Each UHL subject's age is marked with a resolution of years and months. Performance for three subjects with UHL fell within the ± 1 standard deviation boundaries, while the other four fell above one standard deviation of the NH mean. These results indicate that some subjects with UHL performed similarly to age-matched NH control subjects, while others performed quite worse. Interestingly, the two subjects who were aided with a traditional hearing aid fell within the NH boundaries. Additionally, the subject who participated twice in the experiment showed improved performance with her hearing aid (9_HA2*) than initially unaided (8_U*).

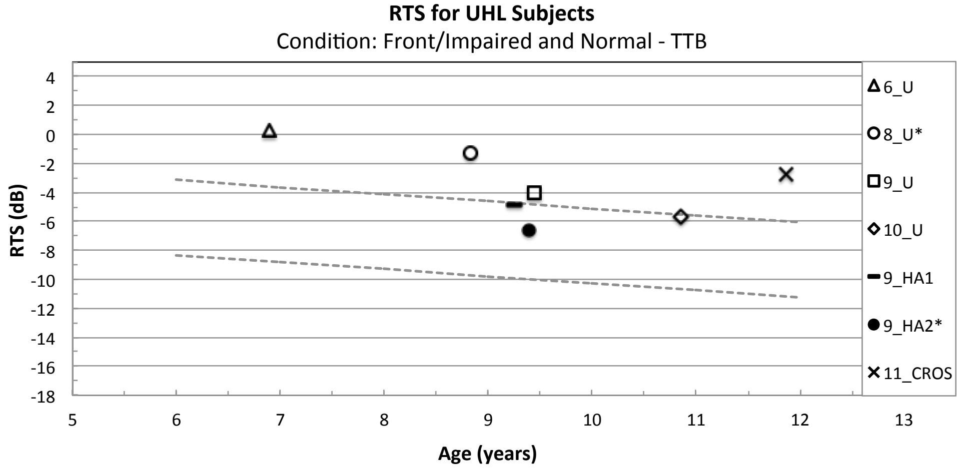


Figure 25. RTS in the presence of a symmetrically placed TTB masker for UHL subjects.

RTS (dB) in the presence of TTB are plotted as a function of age (in years) for UHL subjects. Each subject with UHL is denoted by a unique symbol. Note: 8_U* and 9_HA2* represent the same subject who participated twice in the experiment. Dashed lines represent ± 1 standard deviation from the normal-hearing age means.

Spatial release from masking (SRM) in the symmetrical masking condition was calculated for UHL subjects and is shown in Fig. 26 (see Appendix V for all data). The amount of SRM benefit for four subjects fell within the ± 1 standard deviation boundaries for subjects with NH, while the other three subjects fell just below one standard deviation of the NH mean. Results indicate similar benefit as NH subjects in this condition. Interestingly all three aided UHL subjects fell within ± 1 standard deviation boundaries.

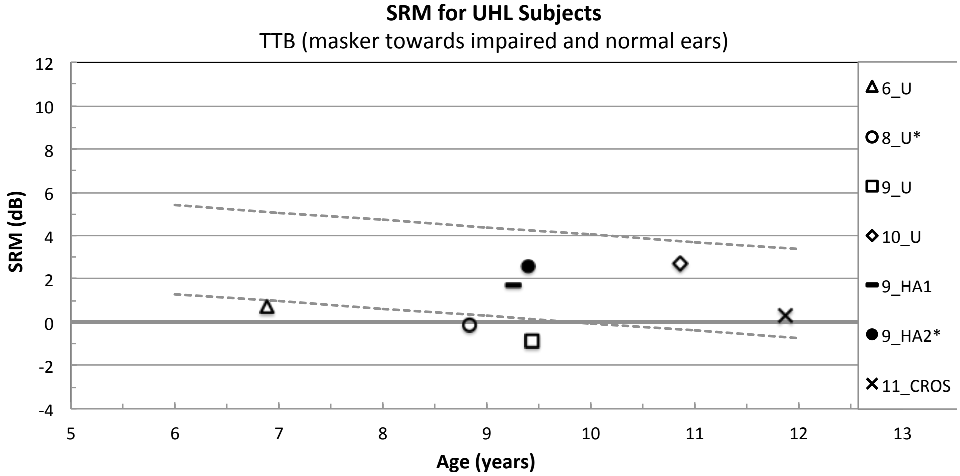
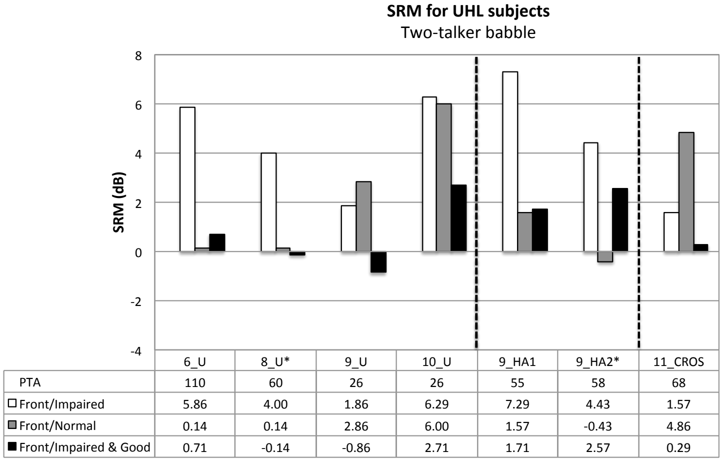


Figure 26. SRM for a symmetrically placed TTB masker for UHL subjects. SRM (dB) is plotted as a function of age (in years) for subjects with UHL. Each subject with UHL is denoted by a unique symbol. Note: 8_U* and 9_HA2* represent the same subject who participated twice in the experiment. Dashed lines represent ± 1 standard deviation from the NH age means. The grey solid line at zero indicates no SRM benefit. Higher numbers indicate more benefit.

To better understand the effect of spatial configuration on SRM with TTB for subjects with UHL, SRM values are re-plotted (from Figs. 18c, 18d, and 26) in an additional figure presented below (see Fig. 27). The effect of spatial configuration on SRM is displayed for TTB across subjects. SRM benefit in spatial configuration Front/Impaired and Normal varied greatly across subjects. Some subjects with UHL demonstrated modest benefit from this symmetrical (±60°) spatial separation (see subjects 10_U, 9_HA, and 9_HA2*), while others showed very little SRM benefit or even a decrement in performance. For all subjects, less SRM benefit was observed in the symmetrical masking configuration when compared to the asymmetrical masking configuration, Front/Impaired. The relationship between the symmetrical masking configuration and the asymmetrical masking configuration, Front/Normal, is not as clear as it differed greatly across subjects.



	6_U	8_U*	9_U	10_U	9_HA1	9_HA2*	11_CROS
PTA	110	60	26	26	55	58	68
□ Front/Impaired	5.86	4.00	1.86	6.29	7.29	4.43	1.57
▨ Front/Normal	0.14	0.14	2.86	6.00	1.57	-0.43	4.86
■ Front/Impaired & Good	0.71	-0.14	-0.86	2.71	1.71	2.57	0.29

Figure 27. SRM for UHL subjects in all masking configurations with masker type TTB.
SRM (dB) for all UHL subjects is displayed for TTB for all three spatial configurations. Spatial configurations are represented by different colored bars: unfilled bars = Front/Impaired, grey filled bars = Front/Normal, black filled bars = Front/Impaired and Good. For reference, the PTA is also provided for each subject. * indicates same subject

3.4.4 Comparisons Across Conditions

3.4.4.1 NH Subjects

Experiment 1 assessed subjects' masked sentence recognition abilities with SSN and TTB in a variety of spatial configurations (i.e., co-located, asymmetric, and symmetric masking paradigms). Average RTS are re-plotted below in summary Figs. 28a (SSN) and 28b (TTB) for NH subjects. Both children and adults performed better in spatially separated conditions (represented by triangle and square symbols) as opposed to co-located conditions (represented by circle symbols). Performance improved as age increased for all conditions. For SSN, the steeper rate of improvement with age in the spatial condition compared to the co-located condition may be due to maturation of binaural processing abilities and growing head sizes, which would tend to increase interaural differences slightly. Performance improved more steeply with increasing age with the TTB versus SSN masker (compare circle and triangle symbols across the two figures). For the symmetrical condition (TTB masker employed), the slope was more shallow (slope =-0.49 dB/year) compared to the co-located (slope = -0.83 dB/year) and asymmetrical (-0.85 dB/year) conditions. When listening in the presence of SSN, children showed adult-like performance by age nine. This was not the case in the presence of TTB, likely pointing to continued maturation of perceptual processing beyond 12 years of age.

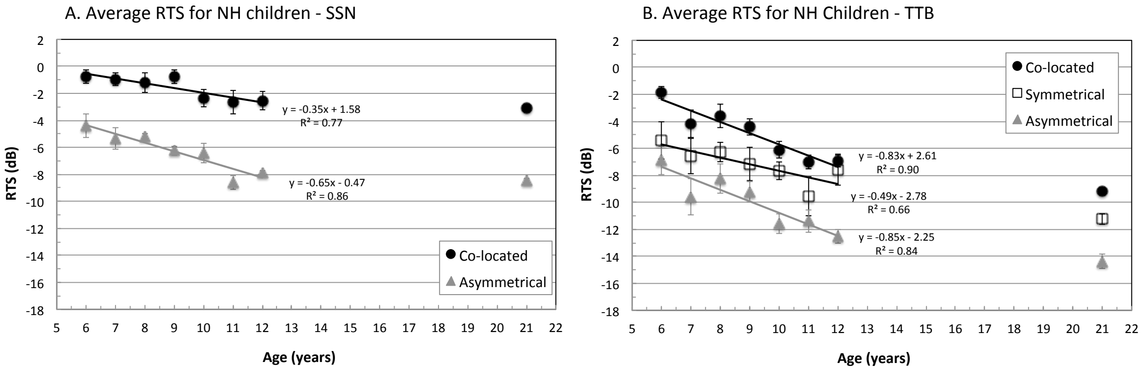


Figure 28. Average RTS for NH subjects for SSN (a) and TTB (b) maskers across various spatial configurations.

Average RTS plotted as a function of age for maskers (a) SSN and (b) TTB across different spatial configurations. Asymmetrical represents the average of conditions Front/Right and Front/Left. Error bars indicate ±1 standard error of the mean. Note: lower numbers indicate better performance.

To more easily compare the developmental slopes across different RTS functions, scores were normalized to the 6-year-old means for each condition (Fig. 29). In doing so, differences in developmental improvements are easily observed across the two masker types. With TTB, the rate of improvement with age (i.e., slope) is nearly identical in the co-located and asymmetrical masking configurations (also hold the steepest slopes compared to the other conditions). This finding of similar slopes indicates that the improvement in performance due to spatial separation was consistent across age. The steep developmental improvements are likely mediated by a subject's ability to take advantage of temporal and spectral fluctuations in TTB and/or improving sound source segregation abilities with real-speech maskers. Conversely, the slopes for SSN (co-located and asymmetrical masking configurations) were not parallel, rather a steeper rate of improvement was observed in the spatial condition (asymmetric SSN). Additionally, the slope for the symmetrically placed TTB was considerably shallower than both asymmetric and co-located TTB.

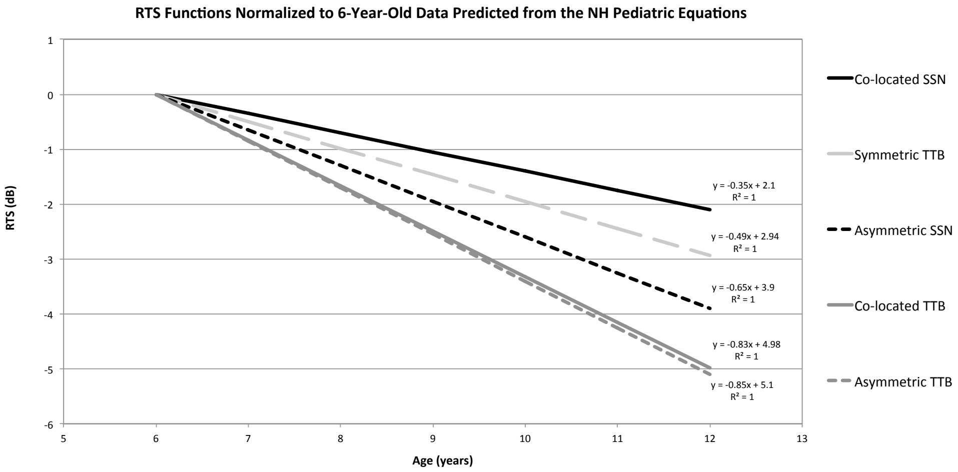


Figure 29. RTS functions normalized to the 6-year-old data for listening conditions employing noise.
Data predicted from the NH pediatric equations.

For both children and adults, TTB was a less effective masker than SSN (see Fig. 30). The reduction of masking effectiveness in the presences of the TTB relative to SSN steadily grew with age (more apparent in the co-located condition). Findings likely indicate that with increasing age children were better able to "listen in the dips" and/or ignore the TTB.

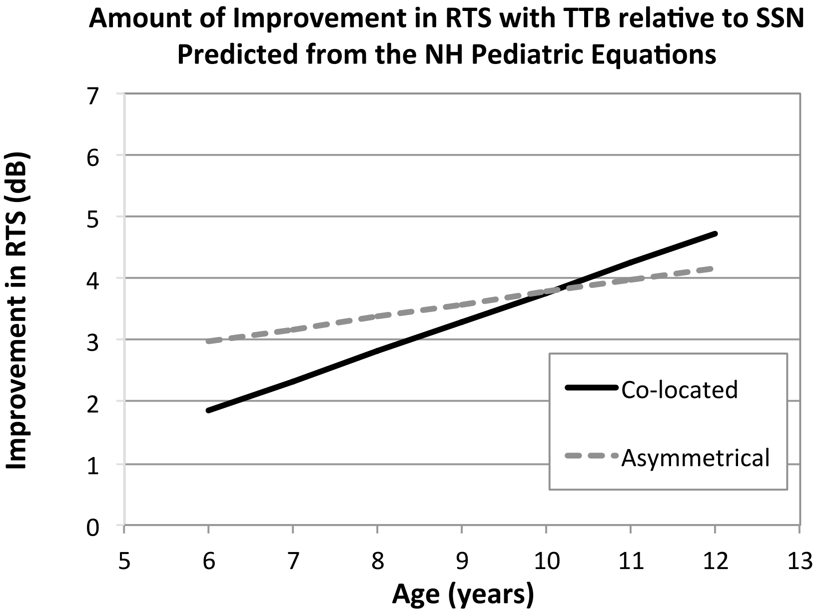


Figure 30. Amount of improvement in RTS with TTB relative to SSN for NH subjects

Average amount of improvement in RTS with the TTB relative to performance in SSN plotted as function of age across different spatial configurations. Asymmetrical represents the average of conditions Front/Right and Front/Left. Data predicted from NH pediatric equations.

Spatial release from masking was calculated to compare performance in the co-located versus the spatially separated conditions (Fig. 31). Data are estimated from the NH pediatric fitted equations. Although there was considerable variability, it appears that average SRM increased only slightly with age in the asymmetrical masking configurations with SSN and remained relatively constant with TTB. Conversely, SRM decreased as a function of age in the symmetrical masking configuration.

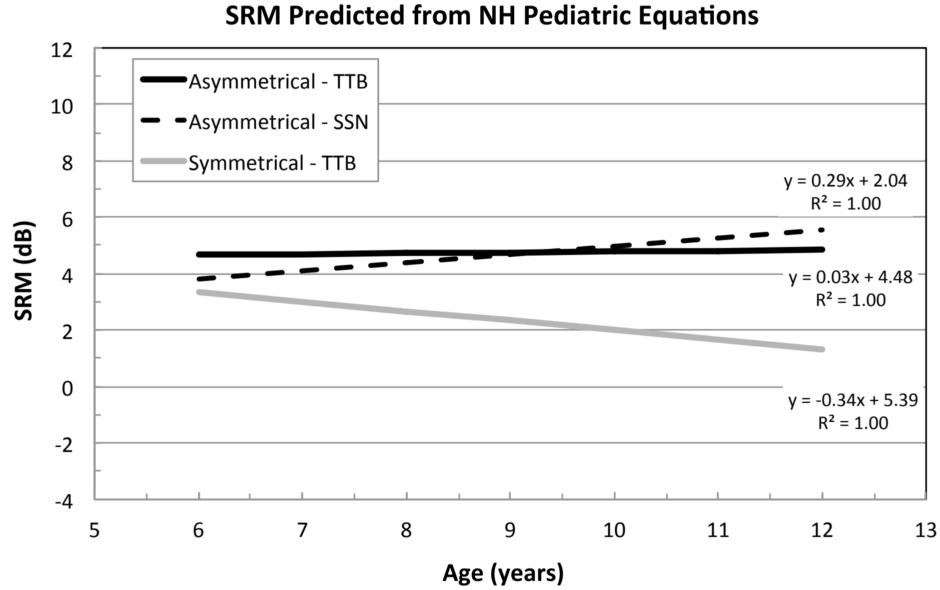


Figure 31. SRM benefit for NH subjects in asymmetrical and symmetrical masking configurations

Spatial release from masking (SRM) plotted as a function of age (in years) across different spatial configurations. Data predicted from NH pediatric equations.

3.4.4.2 UHL Subjects

The subjects with UHL in the current study make up a heterogeneous group, making group-based conclusions challenging. Although none hold statistical significance, several findings from Experiment 1 are clinically interesting and will be summarized below.

To compare children with UHL to NH subjects, standardized scores were derived using the previously described method. In all conditions, there were subjects with UHL who showed poorer performance, falling > 1 standard deviation from the NH mean. In a normal distribution, we would expect that 16% of the scores from members of that group would fall outside the +1 standard deviation boundary. However in this sample of children with UHL, 70% of all the scores fell outside of the +1 standard deviation boundary (see Fig. 32). Furthermore, 45% (compared to the expected 2.5%) of the scores fell outside the +2 standard deviation boundary, highlighting clinically relevant differences between subject groups.

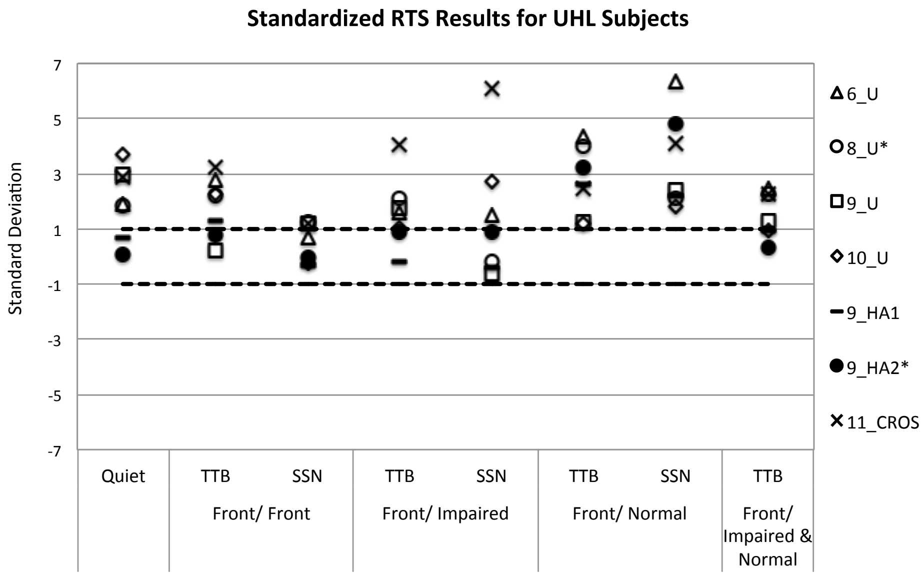


Figure 32. Standardized RTS results for UHL subjects for all listening conditions

Number of standard deviations from the NH mean for each UHL subject across all listening conditions. Note: performance above the mean is reflective of poorer performance. * indicates the same subject.

The deviation from the NH mean depended on the specific listening condition. In conditions of quiet and a co-located target with TTB, most subjects showed poorer performance than NH subjects. Poorer performance in these non-spatial conditions indicates lack of NH even in just one ear can impair sentence recognition in tasks conventionally thought to be mostly monaurally based. All subjects with UHL had scores > 1 standard deviation from the NH mean in the asymmetrical masking conditions Front/Normal with both SSN and TTB, an expected finding given the masker was directed towards subjects' better hearing ear. In other conditions subjects with UHL often showed similar performance when compared to age-matched NH listeners. For example, most UHL subjects showed performance similar in the asymmetrical masking conditions Front/Impaired with both SSN and TTB and in the co-located condition with SSN.

In several conditions, aided subjects (UHL-A) showed improved performance when compared to unaided subjects (UHL-U). For example, aided subjects had better performance in quiet, Front/Front – SSN, and Front/Impaired – TTB.

The amount of improvement in RTS with TTB relative to SSN is displayed below in Fig. 33. By and large, TTB was a less effective masker than SSN for subjects with UHL, as was the case for NH subjects. Findings suggest that subjects with UHL are able to “listen in the dips” and/or ignore the TTB like their NH peers.

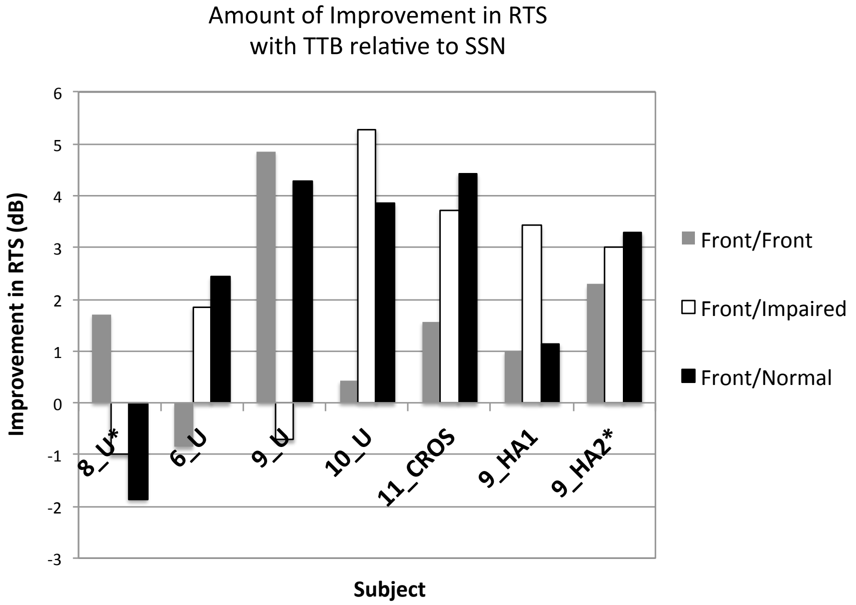


Figure 33. Amount of improvement in RTS with TTB relative to SSN for UHL subjects

Average amount of improvement in RTS with the TTB relative to performance in SSN plotted as function of age across different spatial configurations.

Spatial release from masking was calculated to compare performance in the co-located versus the spatially separated conditions. Standardized scores for UHL subjects are plotted below in Fig. 34. In all conditions, there were subjects with UHL who showed poorer performance than subjects with NH, falling > 1 standard deviation from the NH mean. In a normal distribution, we would expect that 16% of the scores from members of that group would fall outside the -1 standard deviation boundary. However in this sample of children with UHL, 60% of all the scores fell below one standard deviation from the NH mean. Furthermore, 37% (compared to the expected 2.5%) fell below 2 standard deviations, highlighting clinically relevant differences between subject groups. Deviation from the NH mean again depended on the specific listening condition. In condition Front/Impaired – TTB, nearly all UHL subjects showed similar amounts of SRM as NH subjects. Conversely most subjects with UHL fell > 1 standard deviation below the NH mean in conditions Front/Normal and all subjects did so in the symmetric condition, Front/Impaired and Normal.

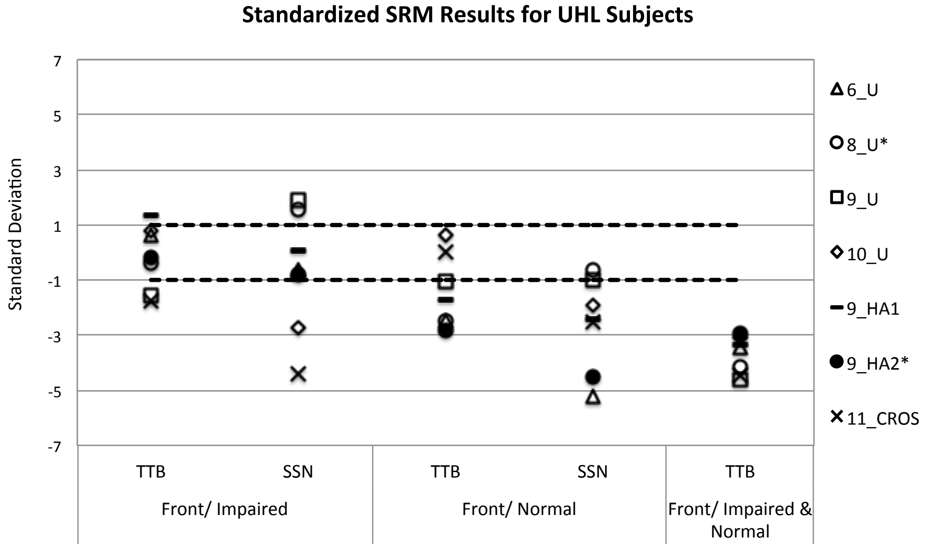


Figure 34. Standardized SRM results for UHL subjects for all spatial listening conditions
Number of standard deviations from the NH mean for each UHL subject across all spatial listening conditions. Note: performance above the mean is reflective of poorer performance. * indicates the same subject.

3.5 Experiment 2

Auditory comprehension abilities were measured in the presence of symmetrically placed (±60°) TTB at varying SNRs.

3.5.1 Test of Narrative Language

3.5.1.1 Subjects

Because there was an odd number of normal-hearing pediatric subjects (n=35), one subject (NH_31, age six) was randomly excluded from the final data analysis for Experiment 2 so that there could be an equal number of subjects in the two presentation orders (n = 17), which was necessary since the order of the first two stories was counterbalanced.

3.5.1.2 Story Equivalency

As mentioned previously in the Methods section, the presentation order of listening conditions remained constant across subjects; the first story was always presented in quiet, the second story was always presented at a +6 dB SNR, and the third story was always presented at the subject's RTS (as obtained in the symmetrical masking condition in Exp. 1). However, the story order for the first two listening conditions was counterbalanced across subjects. One half of subjects in each experimental group (i.e., 9 normal-hearing adults, 17 normal-hearing children, and 4 hearing-impaired children) listened to story 1/McDonalds in quiet and story 2/Shipwreck in the +6 dB SNR condition, whereas the other half listened to story 2/Shipwreck in quiet and story 1/McDonalds in the +6 dB SNR condition. For NH children, gender was distributed fairly evenly across the two presentation orders with 9 males in order 1 and 7 males in order 2. The average age was exactly 115 months (9;7) for the two story-listening condition assignments. The decision to switch the listening conditions assigned to the first two experimental stories was made after initial testing revealed better performance in the +6 dB SNR condition compared to the quiet condition, a somewhat counterintuitive result – see Order 1 in Fig. 35a below. These findings were interpreted as a likely difference in the difficulty of the story or comprehension questions associated with each story (story 1/McDonalds was a more challenging story compared to story 2/Shipwreck) and thus each of the two stories was assigned to different listening conditions for the second half of subjects to counterbalance this effect (see Order 2 in Fig. 35a). The third listening condition at subjects' HINT-C RTS was always assigned to story

3/Dragon, and remained in the final presentation order. Concerns of a story effect were only observed in pediatric subjects. Independent t-test confirmed a significant difference between story 1 and 2 in both quiet, $t(33) = -6.11$, $p < 0.001$, and at +6 dB, $t(33) = 3.5$, $p < 0.001$, listening conditions for NH pediatric subjects. No significant difference was seen between orders 1 and 2 in NH adults for listening conditions, quiet, $t(33) =-1.02$, $p = 0.324$ and +6 dB SNR, $t(33) =0.02$, $p = 0.99$, an expected finding given ceiling level performance in adult subjects in these conditions (see Fig. 35).

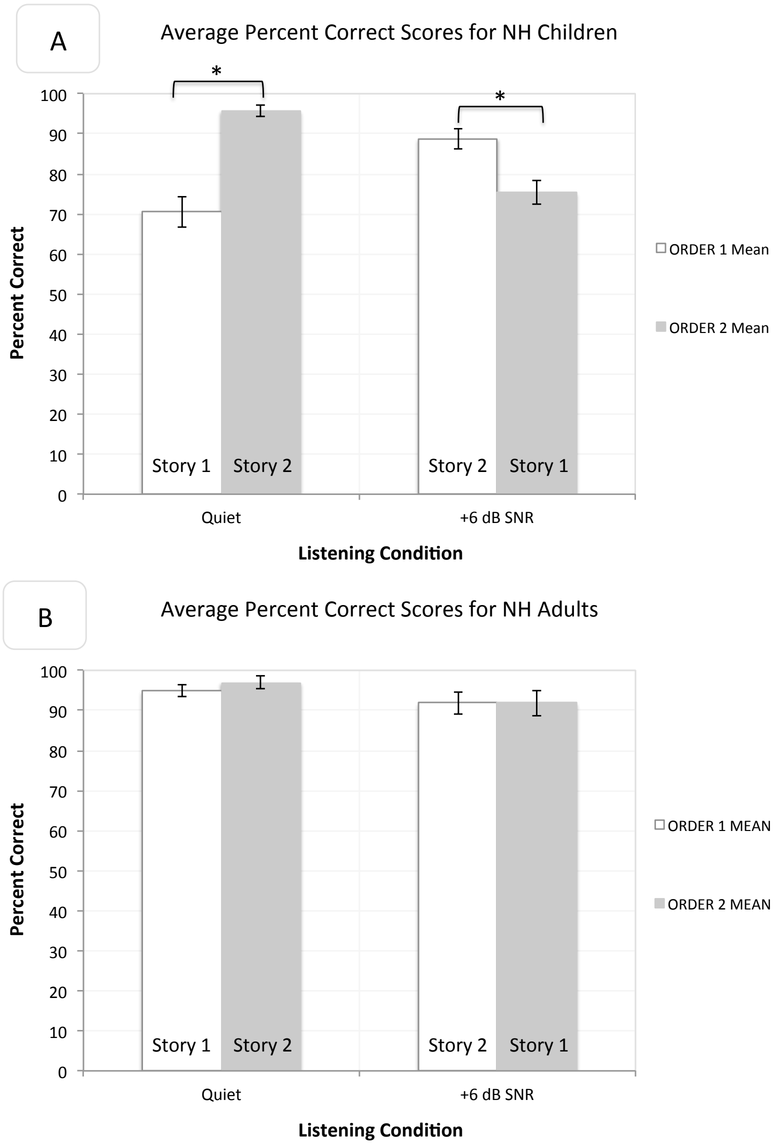


Figure 35. Average percent correct scores for the two listening orders for NH children (a) and NH adults (b).

Mean percent correct scores as a function of listening condition for order 1: McDonalds presented in quiet and Shipwreck presented at +6 dB SNR (white bars) and order 2: Shipwreck presented in quiet and McDonalds presented at +6 dB SNR (grey bars). Fig. 35a displays performance for normal-hearing children; Fig. 35b displays performance for normal-hearing adults. Error bars denote ±1 standard error from the mean.

3.5.2 Comprehension Performance

3.5.2.1 NH Subjects

Percent correct scores were calculated for subjects' answers to the questions from each of the three experimental stories and are displayed for each of the listening conditions below in Fig. 36 (individual data plotted as a function of age in months) and Fig. 37 (average data binned by year of age). It appeared that developmental improvements in performance on the comprehension task occurred mostly in the early years (e.g., between six to seven years old in the quiet condition). After which performance remained constant (i.e., eight to twelve years in quiet condition). Because of this, two-segment linear fits were used to predict the NH means and standard deviation; the break points between the fits were decided through visual inspection of the scatterplots (see Fig. 37).

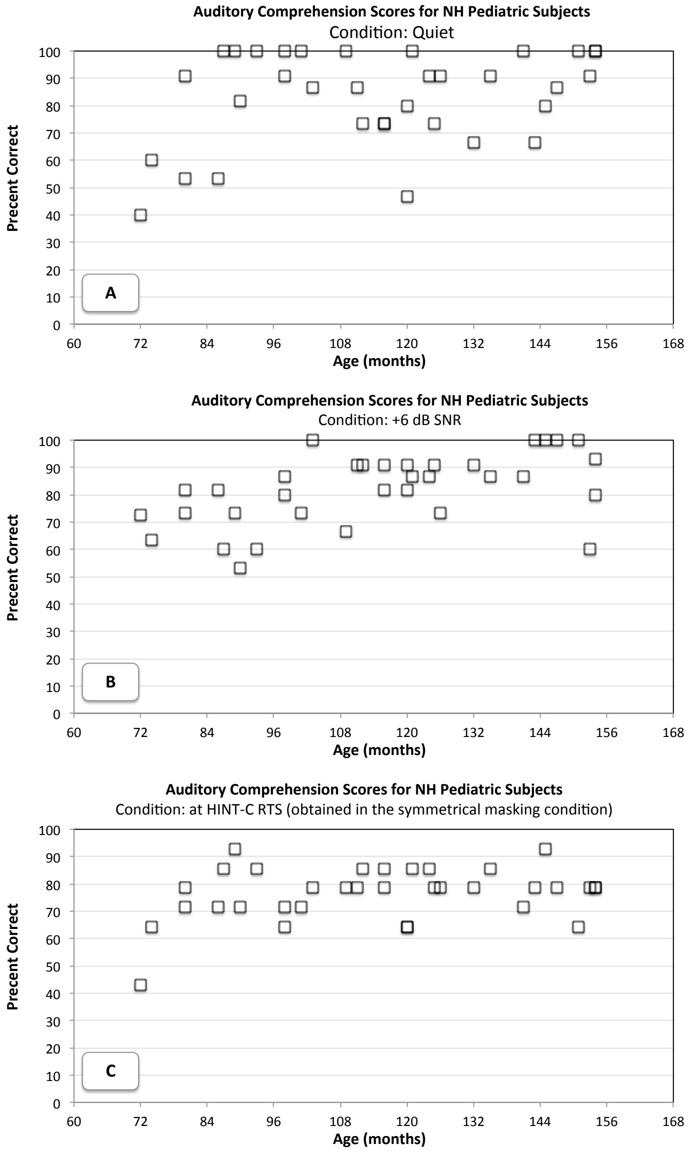


Figure 36. Individual comprehension scores for the three listening conditions for NH subjects.

Percent correct scores plotted as function of age (months) for each of the listening conditions: quiet (36a), +6 dB SNR (36b), and at subjects' HINT-C RTS (36c). Error bars indicate ±1 standard error of the mean.

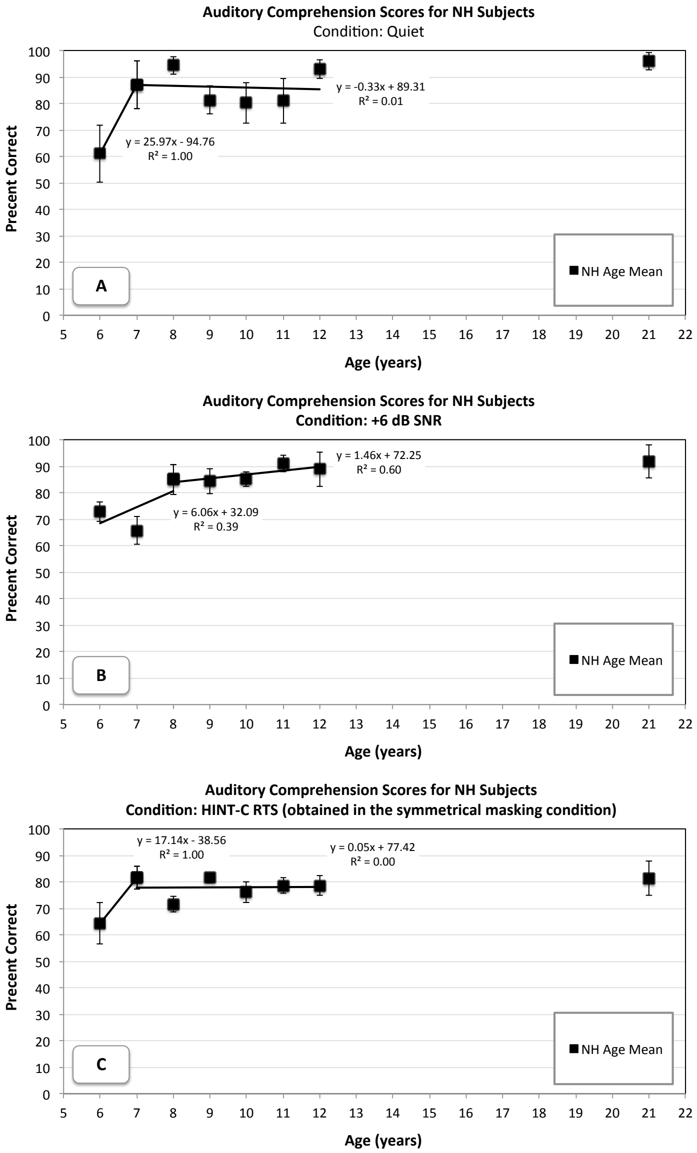


Figure 37. Average comprehension scores for the three listening conditions for NH subjects.

Percent correct scores plotted as function of age (years) for each of the listening conditions: quiet (37a), +6 dB SNR (37b), and at subjects' HINT-C RTS (37c). Error bars indicate ±1 standard error of the mean. Solid lines represent a two-segment linear fit on the average pediatric NH data.

In listening conditions quiet (Fig. 36a) and +6 dB SNR (Fig. 36b), age-related performance differences were found. As age increased from five to 12 years, performance improved. Pearson product-moment correlation coefficients were computed to assess the relationship between age (in months) and comprehension performance. Positive correlation between performance and age was found for both conditions quiet $r(32) = 0.37$, $p = 0.04$ and +6 dB SNR, $r(32) = 0.53$, $p < 0.001$.

In the final listening condition, where data were collected at subjects' HINT-C RTS, all subjects listened to the same story (story 3/Dragon). Recall that the SNR used for story 3 was the HINT-C RTS at which subjects were able to recognize approximately 50% of sentences when presented in symmetrical TTB (NH child average = -8 dB SNR). This RTS value decreased nearly 4 dB as age increased from 6 to 12 years (see Fig. 23 under Exp. 1). This resulted in younger subjects listening at more advantageous (higher) SNRs than older subjects. When equated with the individually determined SNRs, subjects' comprehension scores were fairly constant across age. A Pearson product-moment correlation coefficient was computed to assess the relationship between age (in months) and HINT-C RTS. No significant correlation between RTS and age was found $r(32) = 0.283$, $p = 0.52$. This finding indicates that when matched in SNRs that produce equivalent RTS performance, there was no effect of age on performance.

To illustrate performance across listening conditions, grand means for each age group are displayed below in Fig. 38. When performance of pediatric subjects was averaged across all ages (striped bars), very small differences were observed across listening conditions (83% in Quiet, 82% at +6 dB SNR, 77% at HINT-C RTS). Three pairwise comparisons were conducted to test for significant differences between listening conditions for NH children. After controlling for familywise error, using Holm's sequential procedure, no comparisons were statistically significant. Possible explanations for this high level of performance are as follows: 1) subjects took advantage of gaps in the TTB to better glimpse the target, 2) spatial separation of the target and masker allowed more auditory access to the target signal, and/or 3) subjects used story context and repetition (e.g. a character's name was repeated multiple times throughout a story) to support understanding even when audibility was compromised.

A series of Welch's t-tests were performed to detect any significant differences between the pediatric (striped bars) and adult (black bars) performance across the three listening conditions. After controlling for familywise error, using Holm's sequential procedure, significant differences were detected in the quiet, $t(33) = -4.02$, $p < 0.001$ and +6 dB SNR conditions $t(33) = -3.22$, $p = 0.02$. There was no significant difference detected at HINT-C RTS. This finding again suggests when matched in SNRs that produce equivalent RTS performance, there were no significant differences observed across age.

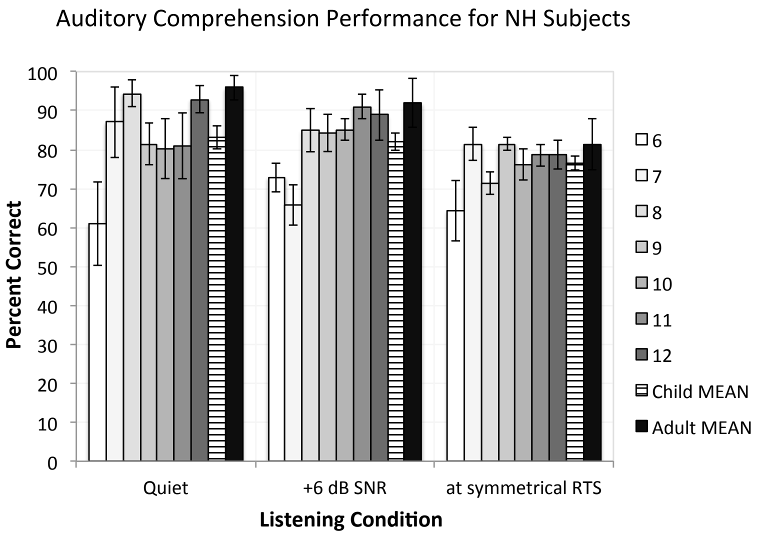


Figure 38. Average percent correct scores of NH subjects for all listening conditions

Average percent correct scores for comprehension questions plotted as a function of age for all listening conditions. Striped bars represent the pediatric average (all ages combined) and the black bars represent the adult average. Error bars indicate ±1 standard error of the mean.

3.5.2.2 UHL Subjects

To compare performance of subjects with UHL to those of NH subjects, comprehension scores are displayed below (see Fig. 39) on three separate scatterplots (one for each listening condition) along with ±1 standard deviation from NH age mean estimated from the fitted equations. As detailed in the Methods section, the square root of the average variance across ages was taken as the standard deviation. The equations from the fitted lines in Fig. 37 were used to predict the means and the ±1 standard deviation for NH pediatric subjects. Each UHL subject's age is marked with a resolution of years and months.

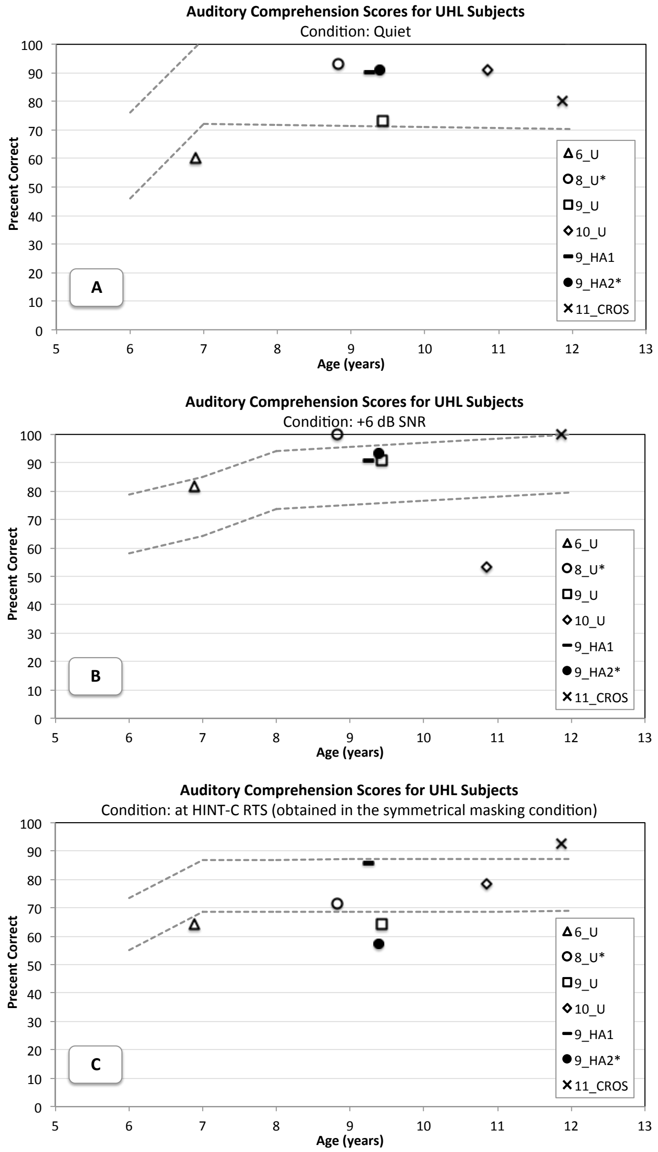


Figure 39. Auditory comprehension scores for UHL subjects for the three listening conditions

Percent correct scores are plotted as a function of age (in years and months) for subjects with UHL for each of the listening conditions: quiet (39a), +6 dB SNR (39b), and at subjects' HINT-C RTS (39c). Each subject with UHL is denoted by a unique symbol. Note: 8_U* and 9_HA2* represent the same subject who participated twice in the experiment. Dashed lines represent ± 1 standard deviation from the normal-hearing age means.

In quiet (Fig. 39a), all but one subject with UHL fell within the ± 1 standard deviation boundaries of the NH age means. Subject 6_U fell just below one standard deviation of the NH mean. It may also be of interest to note that among the three nine-year olds with UHL, the two aided subjects achieved better performance than their unaided counterpart, nearly a 20 percentage point difference in performance, albeit all nine-year-old UHL subjects fell within ± 1 standard deviation boundaries.

In the +6 dB SNR listening condition, all but one subject with UHL fell either within or above (better performance) the ± 1 standard deviation boundaries of the NH age means. This finding reveals that most subjects with UHL performed similarly to NH subjects in this noisy condition, a somewhat surprising finding. It is possible that the +6 dB SNR was too favorable a SNR to detect differences between subject groups. Additionally it is possible that subjects with hearing loss exerted increased listening effort to maintain auditory focus when the story was presented in TTB.

When tested at subjects' individual HINT-C RTS, performance was more variable among UHL subjects. One subject fell above (better performance), three subjects fell within, and three subjects fell below (poorer performance) the ± 1 standard deviation boundaries of the NH age means. Although there was considerable intra-subject variability in this condition, especially noticeable for nine-year olds, performance appears to improve with increasing age, as was the case for children with NH.

To more easily compare performance across listening conditions, comprehension scores are re-plotted and displayed below in Fig. 40 for each UHL subject across listening condition. For nearly all UHL subjects, performance was poorer in the final condition (at HINT-C RTS) when compared to quiet and/or +6 dB. Results suggest that for some subjects with UHL, at more challenging SNRs (average

SNR for UHL subjects = -4 dB SNR), comprehension scores were affected by interfering real-speech maskers.

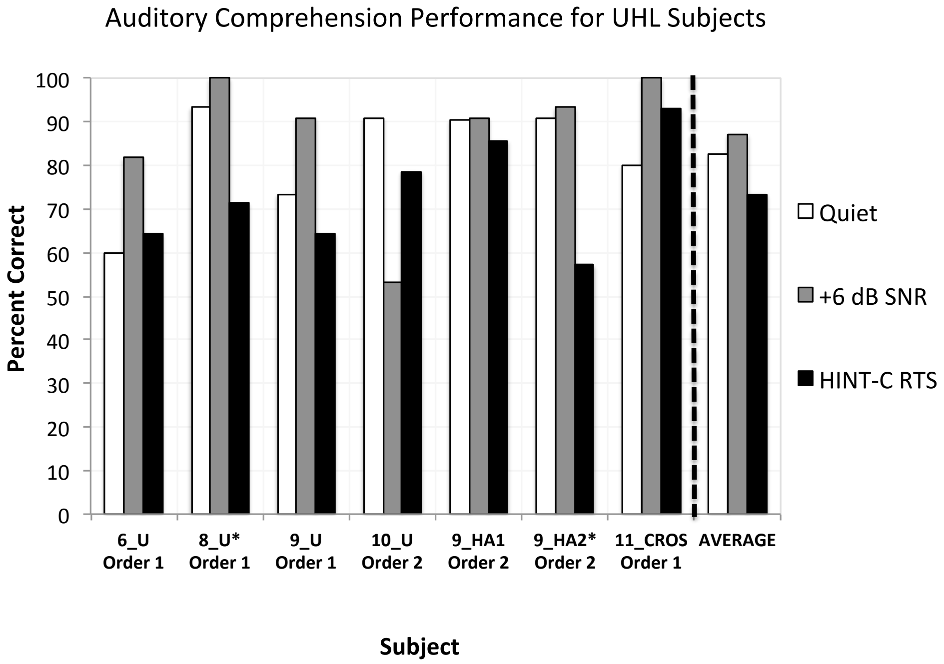


Figure 40. Auditory comprehension scores for UHL subjects for the three listening conditions

Percent correct scores are plotted for each subjects with UHL across the three listening conditions: quiet (white bars), +6 dB SNR (grey bars), and at subjects' HINT-C RTS (black bars). The average bars (right of vertical dotted line) represent the mean of all seven subjects. The presentation order for the first two stories is denoted below each subject's ID; recall the easier story (Shipwreck) was presented +6 dB SNR in order 1 and in quiet in order 2.

CHAPTER 4

DISCUSSION

The goal of the current research project was to enhance our understanding of how school-aged children both with NH and UHL hear in classroom-like noisy environments. The first aim was to better describe the developmental trajectory of NH, school-aged children's auditory perceptual abilities in noisy environments. The second aim was to identify how these abilities differ in school-aged children with UHL, a population that is arguably underserved and understudied. Auditory perceptual abilities were measured for both simple (i.e., sentence recognition) and complex (i.e., comprehension) auditory tasks in two main experiments conducted with school-aged children with NH and UHL and adults with NH. Experiment 1 assessed masked sentence recognition abilities using HINT-C sentence materials in the presence of speech spectrum noise (SSN) and two-talker babble (TTB) in a variety of spatial configurations. Experiment 2 assessed comprehension abilities when listening to oral short stories in the presence of TTB at varying SNRs. Through systematic manipulations of masker type, target-to-masker ratios, and spatial configuration of target and masker, the study's findings add to the current knowledge base on how children with NH and UHL likely function auditorily in acoustic environments that simulate a noisy classroom.

Listening conditions were selected in an attempt to simulate acoustic environments and auditory tasks that would be experienced in a typical classroom. There are a wide variety of interfering signals that could be experienced in a classroom environment. For example, steady noise could come from ventilation systems, nearby construction, snow removal or lawn mowing equipment. Interfering speech signals could come from classmates, teacher's aides, special education teachers, or even volunteers talking in the classroom. All of these interfering signals can make it difficult for a child to understand what a teacher is saying. It is unreasonable to simulate every possible masking scenario in a one investigation. Therefore two idealized interfering sounds, SSN and TTB, were selected for the current study. Speech spectrum noise was created from semi-random white noise that was matched in long-term frequency spectrum and mean square amplitude as the HINT-C sentences used in Experiment 1 (Nilsson, et al., 1994). Two-talker babble was created by adding together one, ten-year-old girl and one, ten-year-old boy speaking a series of nonsense sentences. A variety of spatial conditions were employed to simulate a teacher speaking at the front of the classroom with interfering maskers off to one or both sides. The target signal was always presented from the front (at 0° azimuth) while the interfering signals were placed also in the front or off to one or both sides (at ±60° azimuth). Employing maskers positioned from both the right and left side of the subject was especially important given the focus of the study was on children with UHL, where masker location (i.e., either directed toward normal or impaired ear) greatly affects of performance. In order to more fully define the developmental trajectory of these auditory abilities and to compare UHL subjects' performance to their peers, normative data was collected on large number of NH pediatric subjects. A review of the study's research questions and hypotheses will ensue below.

4.1 Review of Research Questions and Hypotheses

Specific Question 1: As school-age children develop (from six to 12 years of age), do their masked sentence recognition abilities improve?

Hypothesis 1: Given the well-known effect of age on speech reception thresholds (Elliot, 1979; Byrne, 1983; Litovsky, 2005; Garadat and Litovsky, 2007), it is expected that younger children, both with NH and UHL, will exhibit poorer reception thresholds for sentences (RTS) when compared to older subjects in all listening conditions.

The study's findings were in agreement with Hypothesis 1 for NH subjects. A significant and negative correlation was found between age and RTS for NH subjects in all listening conditions. As age increased from six to 12 years, performance improved (RTS decreased). When comparing average performance across age groups (in years), adult-like performance appeared to be achieved by older children (e.g., 11 and 12 years of age) when listening in the presence of SSN. However in TTB, even at 12 years of age, children continued to have poorer RTS when compared to adults.

The current findings are consistent with the developmental psychoacoustic literature in this area showing that younger children have poorer SRTs than older children and adults in the presence of speech interferers (Buss, et al., 1999; Oh, et al., 2001; Johnstone and Litovsky, 2006; Garadat and Litovsky, 2007; Van Deun, et al., 2010; Schaefer, et al., 2012) and speech shaped noise (Hall, et al., 2002). Recall that documented classroom noise levels are highest in classrooms of younger students (Picard and Bradley, 2001). This means younger students, who require a higher SNR, are listening and learning in environments with the poorest SNRs. A current assumption in auditory development research is that the peripheral auditory system (i.e. cochlea and VIIIth nerve) fully matures by six months of age (Buss, et al., 2012). Increased listening difficulties experienced by children in the presence of interfering signals does not appear to be due to an immature peripheral auditory system. Rather, it is widely believed that poor performance on masked speech recognition is due to immature perceptual processing in the central auditory system (Hall, et al., 2002; Leibold, 2012).

Performance improved with age when listening in the presence of SSN; however, the rate of improvement was more gradual than that associated with TTB (for asymmetrical and co-located configurations) (see Fig. 29, page 100). Findings suggest that the differing developmental improvements across masker type are likely mediated by unique auditory/perceptual processes. The slopes for TTB in co-located and asymmetrical masking configurations had the steepest slopes relative to the other conditions and were nearly identical. This finding indicates that the improvement in performance due to asymmetrical spatial separation with TTB (i.e., SRM) is consistent across age. Additionally, these developmental improvements are likely mediated by a subject's ability to 1) take advantage of temporal and spectral fluctuations available in the TTB and/or 2) segregate a speech target from a real-speech masker (TTB may have acted in part as an informational masker in the younger children). Interestingly, the slope for the symmetrically placed TTB was considerably shallower when compared to co-located and asymmetrically placed

TTB. At the present time, there is no clear explanation for this finding. The slopes for SSN in co-located and asymmetrical masking configurations were not parallel; rather a greater rate of improvement as age increased was observed in the spatial condition. This finding may be due to maturation of binaural processing abilities and growing head sizes, which would tend to increase interaural differences slightly (Hall and Grose, 1990). Previous developmental studies on masking level differences (MLDs) have shown that younger children (< 7 years) have smaller MLDs than adults for stimuli of relatively narrow bandwidths (Hall and Grose, 1990; Grose, et. al., 1997).

Given the heterogeneous and small sample of subjects with UHL, statistical analyses to determine the effect of age on RTS performance could not be performed. However, upon visual inspection of the scatterplots for subjects with UHL, it appears that RTS improves with increasing age in most listening conditions. This is especially clear when only inspecting performance for unaided subjects (see Figs. 11, 17, and 25). This area of research warrants more attention, but it does appear that children with UHL may benefit from developmental improvements in performance similarly to their counterparts with NH.

Specific Question 2: Are both children with NH and UHL differentially affected by real-speech and noise maskers?

Hypothesis 2: The majority of research has shown that at equivalent intensity levels, maskers composed of a small number of talkers (i.e., two to three) result in more masking than for noise (Carhart, et al., 1975; Hall, et al., 2002). Thus it is expected that both children with NH and UHL will exhibit higher (i.e., poorer) RTS in the presence of two speech interferers versus speech-spectrum noise masking.

The study's findings were contrary to those predicted in Hypothesis 2 for subjects with NH and UHL. Subjects with NH demonstrated better performance (lower RTS) when listening in the presence of TTB compared to SSN in all spatial configurations. Children of all ages demonstrated improved RTS in the presence of TTB versus SSN and this improvement steadily increased with age. These findings suggest that subjects benefited from temporal and spectral fluctuations in the speech masker to be able to glimpse the speech of the target talker (Feston and Plomp, 1990).

At equivalent SNRs, maskers composed of a small number of talkers have frequently been shown to produce more masking than steady noise, an outcome revealing informational/perceptual masking (Carhart, et al., 1969; Brungart, et al., 2001; Freyman, et al., 2007). Informational masking occurs where there is similarity between the target and maskers (e.g., adult female target and maskers) (Brungart, 2001). However, the masking stimuli employed in this study appeared to produce little of this type of masking. Although the TTB employed in the current study was a less effective masker than SSN, its validity was high. Children routinely listen in environments with an adult speaker and interfering child talkers (e.g., classroom, home, extracurricular activities). The current study simulated this common listening condition by employing an adult male target talker and two child interfering talkers (one ten-year-old boy and one ten-year-old girl).

The present study's finding of improved performance when listening to TTB versus noise is similar to that of Litovsky (2005) who found increased masking in four- to seven-year-olds with speech-noise versus one or two speech competitors. Litovsky (2005) similarly employed target and masker stimuli of different genders, although both were adult speakers. When target and interfering talkers are of different genders, differences in voice quality, pitch, and ongoing fundamental frequency differences between the target and interfering talkers can allow for easy source segregation (Brungart, et al., 2009).

Individual subject data were more variable in the presence of TTB than SSN. Several explanations for this are possible. First, the TTB masker is inherently more variable. A random selection of the masker was chosen on each trial. Moments of silence in the masker (e.g., pauses between words) randomly fell on different words on the target signal, making performance between individual subjects intrinsically more variable. Additionally, it is possible that the ability to take advantage of dips in a fluctuating masker varies across subjects and is only partially explained by chronological age.

Given the heterogeneous and small sample of subjects with UHL, statistical analyses to determine the effect masker type on RTS performance could not be performed. However, it appears that most children with UHL demonstrated improved performance when listening in the presence of TTB compared to SSN. Findings again appear to be contrary to those predicted in Hypothesis 2, as was the case for subjects with NH. Outcomes of this experiment suggest that subjects with UHL may be able to "listen in the dips" (Feston and Plomp, 1990) like their NH peers. These findings need to be confirmed with a larger data set before making definitive conclusions.

Specific Question 3: Does the availability of spatial differences between the target and masking signals improve performance of children with NH and UHL to similar degrees?

Hypothesis 3: Children with hearing loss, even mild in degree, have demonstrated poorer speech-in-noise recognition abilities than children with NH (Crandell, 1993; Ching, et al., 2011). Research has shown that children with UHL show deficits in speech recognition in noise when compared to their NH peers in most spatially separated configurations (Bess, et al., 1986; Ruscetta, et al., 2005). Thus, children with UHL are expected to achieve poorer RTS than age-matched, NH controls in both co-located and spatially separated conditions.

Since only a small number of subjects with UHL participated in the current experiment, analyses to determine statistical significance were not performed. Instead standardized scores for UHL subjects were derived and compared to the distribution of scores obtained from NH subjects. In all experimental listening conditions (with and without spatial cues and with both masker types) there were subjects with UHL that fell outside the ±1 and 2 standard deviation boundaries of the mean performance of age-matched subjects with NH. Across all eight listening conditions, 70% percent of UHL subjects' RTS' fell outside ±1 standard deviation boundaries of the NH mean and 45% fell outside ±2 standard deviation boundaries of the NH mean. These findings partially support those predicted in Hypothesis 3.

Most listeners with UHL demonstrated differences in quiet when compared to performance of NH subjects. When averaged across ages, children with NH had quiet thresholds equal to 14.6 dBA, whereas subjects with UHL had a mean threshold of 20.8 dBA. Interestingly the two subjects with UHL who wore a traditional hearing aid had much lower thresholds in quiet when compared to the others (16.9 and 14.3 dBA). Their thresholds were more similar to the mean of NH subjects (14.6 dBA) versus unaided UHL subjects (24.3 dBA). The third aided subject who was utilizing a CROS hearing aid system had a quiet threshold of 21.7 dBA, which was more similar to the other unaided subjects (24.3 dBA). It appears that the two children with traditional hearing aids were benefiting from binaural summation (Hirsh, 1948), a binaural process unavailable to listeners using a CROS system or to unaided subjects with UHL. Binaural summation at threshold refers an improvement in threshold when listening with two ears compared to only one (Hirsh, 1948). These differences in quiet between the NH and UHL groups are similar to those obtained by Rothpletz, et al. (2012), who found significant differences (4.5 dB) between NH and UHL adult listeners in co-located listening conditions in the sound field. Rothpletz, et al. (2012), also conjectured that differences could be explained by a statistical advantage of having two independent looks versus a single look of the stimuli (Zwicker and Henning, 1985; Schooneveldt and Moore, 1989).

In non-spatial conditions (i.e., co-located), differences between NH and UHL subjects appeared to depend on the masker type. Most subjects with UHL fell above one standard deviation of the NH mean (i.e., performed more poorly) when listening in the presence of TTB, but performed similarly to NH subjects when listening in the presence of SSN.

In asymmetrical masking conditions, results depended on the side of the masker in relation to the better-hearing ear. When the masker was directed towards subjects' good/normal ear, all subjects with UHL fell above (poorer performance) one standard deviation of the NH mean (results compared to the Front/Side condition). Conversely, when the masker was directed towards subjects' impaired ear, many subjects fell within the ±1 standard deviation boundaries of the NH mean (results compared to the Front/Side condition). The most obvious exception to this was the subject utilizing a CROS hearing system. This subject had a RTS greater than four standard deviations above the NH mean in the presence of TTB, and greater than six standard deviations above the mean in the presence of SSN in the spatial condition Front/Impaired (masker directed toward subjects' hearing-impaired ear). This finding suggests disadvantages when listening with a CROS hearing aid system in the above listening conditions, a finding consistent with the literature (Updike, 1994). In the symmetrical masking configuration the results were mixed. About half of subjects with UHL showed similar performance to NH subjects, whereas the other half fell above (poorer performance) one standard deviation of the NH mean.

Hypothesis 4: Research shows that children as young as three years of age with NH perform better when listening in conditions that employ spatial separation between target and masking signals in both asymmetric and symmetric configurations (Litovsky, 2005; Garadat and Litovsky, 2007; Cameron and Dillon, 2007; Ching, et al., 2011; Lovett, et al., 2012). However, adults with UHL do not realize as much of this benefit, especially in conditions when the noise is directed towards the subject's impaired ear (Ruscetta, et al., 2005). Therefore, it is hypothesized that SRM benefit will be realized by all children, but in fewer conditions and to a lesser degree by children with UHL.

The study's findings are consistent with those predicted in Hypothesis 4. Subjects with NH had improved performance (lower RTS) in all spatial listening conditions (i.e., when the target was presented from the front loudspeaker and the masker from one or both loudspeakers) compared to co-located conditions (i.e., both the target and masker were presented from the front speaker). Additionally, all NH subjects benefited from spatially separating both masker types (SSN and TTB) from the target talker. This benefit of spatially separating the target and masking signals is referred to as spatial release from masking (SRM).

Normal hearing subjects demonstrated SRM benefit in all listening conditions. When averaged across age, the amount of SRM for asymmetrically placed SSN and TTB was 4.7 dB and 4.8 dB, respectively. Results are consistent with those obtained by Lovett, et al. (2012) who measured speech reception thresholds in the presence asymmetrically placed (± 90 ° azimuth) pink noise across three- to seven-year-olds with NH and found on average 5 dB of SRM. The amount of SRM remained constant for asymmetrically placed TTB, increased slightly with age for asymmetrically placed SSN, and decreased slightly for symmetrically placed TTB. A possible explanation for the decreasing amount of SRM with the symmetrically placed TTB is that the large amount of SRM in the younger children was due to release from both energetic and informational masking in the co-located condition, whereas the small SRM observed in the older children was due to a release from only energetic masking in the co-located condition.

Although the amount of SRM decreased slightly with increasing age in the symmetrically placed TTB masker, NH pediatric subjects did indeed demonstrate SRM in this challenging condition. In the symmetrical masking configuration (masking signals directed towards both the right and left ears), there is no long-term better ear advantage at either ear (as is the case with the asymmetrical masking configuration). Instead listeners rely on "better-ear glimpses" of the target signal, which vary ear to ear as a function of frequency and time (Brungart and Iyer, 2012). Normal-hearing adult listeners have demonstrated highly efficient abilities to extract information from these better ear glimpses, achieving SRM on the order of 6 dB (Brungart and Iyer, 2012). Normal-hearing pediatric listeners (three to 12 years of age) have demonstrated SRM in this symmetrical masking configuration on the order of 3 dB when listening to words in the presence of multitalker babble (Ching et al., 2011). In the current study, when averaged across age, NH pediatric subjects obtained 2.3 dB SRM in this symmetrical masking condition, which is in close agreement to results obtained by Ching, et al. (2012). It may be such that younger children are less able than older children and adults to quickly integrate information gained from better-ear glimpses due to immature sound source segregation and/or selective attention abilities (Leibold, 2012).

Past studies have reported less spatial release from a noise masker in children than adults (Johnstone and Litovksy, 2006; Van Deun, et al., 2010), whereas others have found no significant effect of age with either a noise masker (Litovsky,

2005) or speech masker (Garadat and Litovsky, 2007; Ching, et al. 2011). Studies that have found significant differences in the amount of SRM across age have employed older children (older than five years) in the presence of noise (Vaillancourt, et al., 2008) or speech interferers (Cameron and Dillon, 2007). Findings of significant age effects in these populations may be due to increased reliability of the older subjects' thresholds, whereas for younger subjects inter-subject variability is typically high making it more difficult to obtain statistically significant findings. Litovsky, et al. (2006) found a significant interaction between masker type and age. Children aged five to seven years showed significantly less SRM than adults with an amplitude modulated noise masker and significantly more SRM than adults with a reversed-speech masker. The current findings add to the literature in this area highlighting that the amount of SRM afforded to a listener depends on a variety of factors such as type of masker, spatial configuration, and in some conditions age of subjects. Furthermore, the present study supports previous studies showing that children with NH are able to benefit from spatial separation of a target from a competing signal at a young age.

Spatial release from masking was calculated for subjects with UHL. Subjects with UHL showed high variability in the amount of SRM benefit, which appeared to be dependent on spatial configuration and masker type. While most subjects with UHL demonstrated SRM (> 0 dB) in many listening conditions, the amount of benefit was often lower than that obtained by subjects with NH this was especially true for spatial configuration, Front/Normal. Across the five spatial conditions tested, 60% of UHL subjects' SRM values fell below the one standard deviation boundary of the

NH mean (i.e. less SRM) and 37% fell below two standard deviations of the NH mean. In spatial configurations, Front/Impaired (noise directed towards subjects' hearing-impaired ear), three subjects had SRM values that fell above the one standard deviation boundary of the NH mean indicating greater SRM than NH subjects. In this condition (Front/Impaired), subjects with UHL heard the masker at a reduced sensation level compared their NH peers because of their hearing loss, which may have given them a slight SNR advantage. The majority of findings appear to support Hypothesis 4; however, a larger data set is needed to be able to make more definitive conclusions.

Specific Question 4: Does a real-speech masker differentially affect comprehension abilities of children with NH and UHL?

Hypothesis 5: It is well understood that children perform more poorly than adults on a variety of speech-perception measures in noise (Finitzo-Heiber and Tillman, 1978; Elliot, 1979; Nitrrouer and Boothroyd, 1990). Limited evidence suggests that auditory comprehension performance may be more deleteriously affected by poor acoustics than speech recognition (Klatte, et al., 2010b; Valente, et al., 2012). Thus it is expected that as SNR becomes more challenging, auditory comprehension performance will decrease for both children with NH and UHL.

The study's findings were contrary to those predicted in Hypothesis 5. It was assumed that as SNR became more difficult from story one to story three, comprehension performance would decrease for all subjects. It was possible that at challenging SRNs subjects would miss information early on the story leading to a later misunderstanding or that subjects would simply fatigue part way through the story. Instead little difference was observed between listening conditions for NH pediatric subjects (averaged across age). Normal-hearing children maintained high levels of performance regardless of the SNR tested, even in the final condition, which utilized the SNR at which subjects were theoretically able to recognize 50% of the words in a sentence (i.e., HINT-C RTS). It should not be concluded that SNR does not affect comprehension performance; rather in the specific listening conditions employed in the current study large differences related to the SNRs tested were not found. The present study's results differ from those reported in the literature. Most studies have shown that comprehension decreases as the listening environment becomes more challenging (e.g., as noise levels and reverberation times are increased) (Klatte, et al., 2010b; Valente, et al., 2012). Possible explanations for the high level of performance across SNRs observed in the current study are considered. First, it is possible that subjects were able to take advantage of gaps in the TTB to better glimpse the target speaker. Second, it is likely that spatial separation of the target and masker allowed subjects to hear the target even when the noise levels increased. Additionally, subjects likely used story context and inherent repetition (e.g., the name of a character was repeated several times throughout a story) to support understanding even when audibility was compromised.

Hypothesis 6: Children with UHL have demonstrated poorer scores on tests of language comprehension and oral expression when compared to normal-hearing peers (Lieu, et al., 2010). They also exhibit abnormal narrative skills (Young, et al., 1977) and specific academic difficulties related to reading comprehension and vocabulary (Blair, et al., 1985). If these findings also translate to auditory comprehension skills, it is hypothesized that children with UHL will exhibit poorer auditory comprehension abilities compared to NH controls in all listening conditions.

The study's findings were largely contrary to the predictions made in Hypothesis 6. By and large, most children with UHL performed similarly to age-matched, NH controls (falling within or close to ±1 standard deviation of the NH mean) in all listening conditions. Findings indicate that in quiet and at a commonly observed classroom SNR (+6 dB) most of the children with UHL in this study were able to perform similarly to their NH counterparts on the experimental auditory comprehension task. Even when the SNRs became more challenging with story 3 (average SNR for UHL subjects = -4 dB SNR; NH subjects = -8 dB SNR), differences between NH subjects were only apparent for three subjects with UHL. It is hypothesized that greater differences would have been observed between subjects with NH and UHL had more challenging SNRs been used for UHL subjects.

For nearly all subjects with UHL the poorest comprehension performance was obtained in the final listening condition where the most challenging SNR was employed (see Fig. 40, page 118). It is worth noting that NH subjects listened in more challenging SNRs than subjects with UHL by approximately 4 dB (albeit these SNRs produced equivalent sentence recognition performance). Findings may suggest that some subjects with UHL were experiencing a resource shortage in this complex auditory task. It is possible that some subjects with UHL needed to devote more mental resources to maintain auditory focus on the target talker than their NH peers and consequently had fewer resources left for other cognitive tasks like auditory comprehension and short- and long-term storage of information (Klatte, et al., 2010; Picard and Bradley, 2001).

The current study did not directly measure listening effort; however, it was clearly visible to the researcher that all subjects (with NH and UHL) became more focused and attentive during the final story, which was presented at the most challenging SNR. Often any fidgeting stopped, eye gaze moved to the front speaker, and intense concentration was observed. It is theoretically possible that UHL subjects were employing coping mechanisms to a greater degree than their NH peers in order to maintain high levels of performance. This area of research warrants further investigation. The first step would be to replicate the study's findings with a larger subject pool.

4.2 Unaided versus Aided Subjects

Although there were too few subjects with UHL to draw any firm conclusions regarding the effects of amplification on performance, results of the two groups (unaided and aided) will be discussed here. In total, four subjects participated in the project unaided (UHL-U) and three subjects aided (UHL-A). Recall that one subject participated twice in the experiment, once unaided (8_U*) and second time aided (9_HA2*). In the aided group, two subjects wore traditional hearing aids and one subject used a CROS hearing aid system.

In Experiment 1, UHL subjects' standardized RTS and SRM values were compared to the distribution of NH scores. For the four unaided subjects, only 19% (6 of 32) of their RTS values (across all eight listening conditions) fell within the ±1 standard deviation boundaries of the NH mean. In contrast, for the two aided subjects who wore a traditional hearing aid, 69% (11 of 16) of their RTS values fell within the ±1 standard deviation boundaries of the NH mean. This is in stark contrast to 0% (0 of 8) for the subject using the CROS hearing aid system. In fact, for this subject (11_CROS) 88% (7 out of 8) of her RTS values fell more than 2 standard deviations above (poorer performance) the NH mean, indicating clinically significant differences. Both the unaided and aided (with traditional hearing aid) subjects had similar distributions of SRM scores across the listening conditions (45% for unaided versus 40% for traditional hearing aid users) falling within the ±1 standard deviation boundaries of the NH mean or above one standard deviation of the NH mean (better performance).

The subject who participated twice in the experiment provides as an interesting case study for studying the short-term effects of fitting amplification at a late age (7;10). This subject demonstrated improved performance (mean = 3 dB; range = 2-7 dB) in six out of eight experimental listening conditions with the use of a hearing aid versus unaided. For five of these six conditions, hearing aid use moved the subject's RTS values into the ±1 standard deviation boundaries of the NH mean. This subject's age did increase by nearly seven months between test dates, but the differences observed (with and without her hearing aid) were larger than could be explained by developmental effects alone. The two conditions where RTS performance was worse with the use of her hearing aid were Front/Impaired – SSN (1 dB worse) and Front/Normal – SSN (3 dB worse). Amplification via a traditional hearing aid allowed for improved sentence recognition in a variety of listening conditions (different spatial configurations and masker types) for this subject (evident despite being fit with a hearing aid at a later age). Findings should be replicated on a larger data set before making any definitive conclusions; however, the current results are encouraging.

4.3 Study Limitations

The current study had several limitations. First, the sample for the UHL subject group was heterogeneous and small. Unilateral hearing loss subjects were of differing ages, had various degrees of hearing loss, and were of various ages at hearing loss identification. Furthermore, aided subjects were fitted with different amplification devices, at differing ages, and had varying lengths of amplification use. There were additionally several subjects that were not ideal test subjects for a variety of reasons. One subject (9_U) had a mild amount of hearing loss in her better ear (at two frequencies). Another subject (6_U) was diagnosed with pervasive developmental disorder – not otherwise specified, a developmental disorder that can affect social behavior, communication, and attention/interests. Additionally, subject (8_U*/9_HA2*) participated in the experiment twice, once unaided and again nearly seven months later utilizing her hearing aid. These subjects were included in the current project and group interpretations were made with caution.

In the normal-hearing subject group, six subjects had a history of receiving speech-language services before the age of three and one of these children received services through five years of age. Although none had a current diagnosis of a speech-language disorder and all passed a standardized language screening measure before participating in the study, it could be argued that not all normal-hearing subjects were typically developing and that the study design could be strengthened if every subject in the normal-hearing control group was unquestionably also typically developing.

Experiment 2, which investigated auditory comprehension abilities, attempted to task subjects in ways that were representative of a typical classroom environment: SNRs measured in actual classrooms were used, a realistic speech masker was employed, representative spatial relationships between target and competing speech signals were maintained, and the common classroom demand of answering questions about an orally read story was the experimental task. Despite all of these efforts to create an ecologically valid test environment readers are reminded that testing occurred in a sound-treated room, which lacked reverberation typical of a classroom. Additionally, visual cues were removed from the tasks. Most typically, children would have intermittent access to facial expressions and lip movements of the teacher and younger children would likely have picture cues provided in books to facilitate understanding. Future studies should be designed to test children in conditions with reverberation typical of real classrooms with and without the provision of visual cues.

The short stories used in Experiment 2 were selected mainly because they were appropriate for children across a wide age span. However, the stories and corresponding questions proved to differ in difficulty making comparisons of listening conditions more challenging. Future research is needed to develop a standardized story corpus for school-aged children with a plethora of stories and questions equated for difficulty across age. Preferably some of these stories would be developed in such a way where missing information early on in the story would preclude understanding later in the story. Stories created in this way would allow researchers to more closely examine the effect of peripheral hearing loss on comprehension abilities.

4.4 Future Research

The short-term goal for the current research project is to increase subject enrollment numbers for the UHL group. Initial results for this group are intriguing, but more subjects are needed to make any definitive conclusions based upon statistical significance. Long-term investigation with this unique subject group should focus on the effect of amplification. Does amplification ameliorate some of the auditory difficulties experienced in this subject group? Do auditory benefits translate to improved classroom performance? Are certain amplification devices (e.g., hearing aid, CROS system, bone anchored hearing aid, cochlear implant) more beneficial than others? Does age of diagnosis and intervention affect outcomes? These are questions that the audiology community has been grappling with since the early 1980s and remain unanswered. It is imperative we find the answers to these questions so the more than three quarters of a million children with UHL in the US can be better served.

4.5 Summary and Conclusions

Sentence recognition (Exp. 1) and auditory comprehension abilities (Exp. 2) of young adults with normal hearing (NH) and school-age children with NH and unilateral hearing loss (UHL) were tested in a mixed design. In Experiment 1, subjects' sentence recognition abilities were measured in the presences of speech spectrum noise (SSN) and two-talker babble (TTB) in a variety of spatial configurations (co-located and spatially separated). For NH subjects, RTS improved with increasing age (six to 12 years old) in all listening conditions. The growth of improvement across age depended on the masking situation. SSN proved to be a more effective masker than TTB in all listening conditions, indicating subjects were able to take advantage of spectral and temporal fluctuations available in the TTB employed in the current study. Furthermore, RTS appeared to be adult-like by approximately 12 years of age for SSN, but were still immature at this age for TTB. Findings indicate continued immaturity in perceptual processing in the central auditory system in school-aged children.

Performance of UHL subjects depended heavily on spatial location of the masker signal; subjects performed best when masker was directed towards their impaired ear and worst when directed towards their normal-hearing ear. When collapsed across all listening conditions a majority of UHL subjects' RTS fell outside ±1 standard deviation from the NH mean and nearly half fell outside ±2 standard deviations from the NH mean, indicating poorer performance. Some subjects with UHL; however, performed equally well as their NH peers, particularly when aided with a traditional hearing aid.

In Experiment 2, subjects' auditory comprehension abilities were measured in the presence of TTB in a variety of SNRs. When averaged across age, NH subjects performed similarly across the different listening conditions, seemingly unaffected by higher levels of noise. Most UHL subjects had similar performance to the NH subjects in the comprehension task, suggesting that audibility of the target signal may be the driving factor behind successful comprehension.

The findings of the current study contribute towards improving our understanding of both simple and complex auditory abilities of school-aged children with NH and UHL in classroom-like, noisy environments. The study found clinically significant differences between the auditory perceptual abilities and quality of life scores of children with NH and UHL. Furthermore, the study's findings hint at potential improvements in both auditory perceptual abilities and quality of life scores in aided compared to unaided children with unilateral hearing loss.

APPENDICES

APPENDIX A

NORMAL-HEARING PEDIATRIC SUBJECTS' DEMOGRAPHIC INFORMATION

RACE

White	29
Black or African American	5
Asian	0
Native Hawaiian or Other Pacific Islander	0
American Indian or Alaska Native	1
Other	0

OTHER KNOWN LANGUAGES

Ukranian	1
Portuguese	1

GRADE

K	4
1	3
2	4
3	6
4	4
5	6
6	4
7	4

HANDEDNESS

Right	32
Left	3

RESIDENCY

Amherst, MA	16
Belchertown, MA	7
Chicopee, MA	2
Easthampton, MA	2
Greenfield, MA	3
Ludlow, MA	1
Northampton, MA	2
Shutesbury, MA	1
West Springfield, MA	1

HIGHEST LEVEL OF MATERNAL EDUCATION

High School	2
Associates Degree	7
Bachelors Degree	2
Masters Degree	16
Doctoral Degree	8

MARRITAL STATUS

Married	31
Divorced	4

APPENDIX B

UHL SUBJECTS' DEMOGRAPHIC AND ACADEMIC INFORMATION

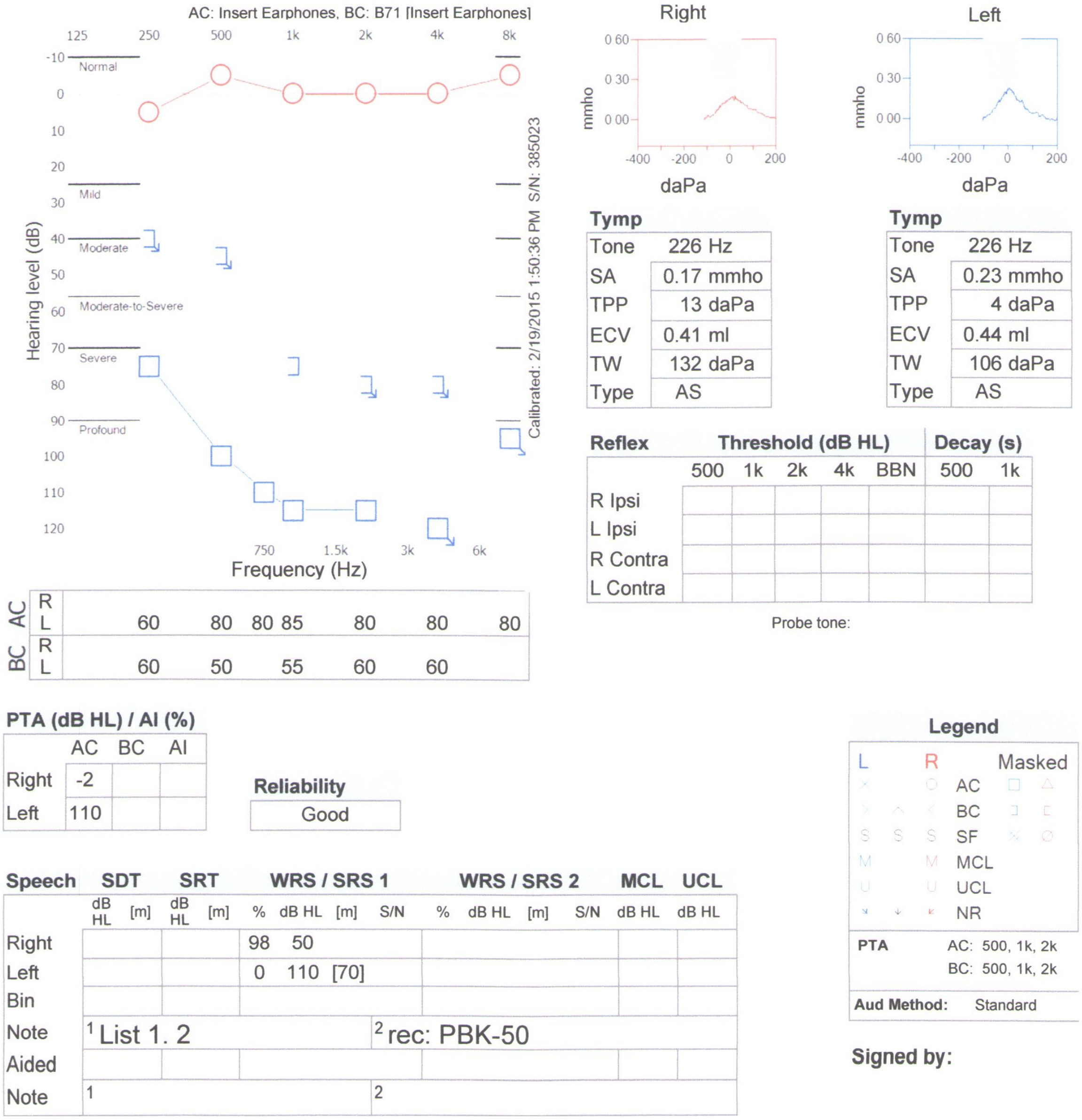
	DEMOGRAPHICS										ACADEMIC INFORMATION (PER PARENT REPORT)								
Subject Code	Grade	Race	First Language	Handedness	Race	First Language	Other Known Langauges	Hometown, State	Highest Maternal Level of Education	Parents' Marital Status	Academic Performance	Excels at	Needs Improvement in	Grade Repetition	Teacher Comments	Special School Services	Educational Audiology Services	Academic Concerns
6_U	3	White	English	Right	White	English	No	Millbury, MA	Associates	Married	Average	Art	None	No	Good listener; Follows directions; Takes pride in work	IEP SLP (2x/ week) Teacher Of the Deaf (TOD) (2x/ week) Social skills group (2x/ week) Home services (2x/ month)	Ed. Aud. trained TOD; Classroom evaluation	No
8_U*	K	White	English	Left	White	English	No	Methuen, MA	Associates	Married	Average	Spelling	Math	No	Excellent	504 Plan FM Preferential seating	FM Classroom evaluation	No
9_U	3	White	English	Right	white	English	No	Newton, MA	Graduate	Married	Above average/ Average	Reading; Science	None	No	Hard working; Puts forth high effort; Participatory	IEP; 504 Plan FM SLP (1x/ week) - discontinued Jan 2014	none	Yes
10_U	5	White	English	Right	white	English	no	Southbridge, MA	Hgh School	Married	Below average	None	All, especially reading	No	Puts forth best effort	IEP SLP	none	Yes
9_HA1	6	White	English	Right	White	English	French	Framingham, MA	Masters	Married	Average	Writing	None	No	Excellent; Very engaged and outgoing; Well on track for age level academically	none	none	No
9_HA2*	3	White	English	Left	White	English	No	Northbridge, MA	Associates	Married	Average	Spelling; English	Math	No	Easily distracted; Hard to keep on task	504 Plan FM Preferential seating	Classroom evaluation	No
11_CROS	4	White	English	Right	White	English	No	Millbury, MA	Associates	Married	Above average	Art; Writing; French	None	No	Insightful, quiet and shy, advanced, artistic, performs well; Gifted in writing and art; Can be distracted	504 Plan Preferential seating Educational audiologist consultation	Teacher in-services Annual check-in with student	yes (declining math abilities)

Same Subject

APPENDIX C

UHL SUBJECTS' HEARING TEST RESULTS

6_U



AC	R							
	L	60	80	80	85	80	80	80
BC	R							
	L	60	50		55	60	60	

Tymp (Right)

Tone	226 Hz
SA	0.17 mmho
TPP	13 daPa
ECV	0.41 ml
TW	132 daPa
Type	AS

Tymp (Left)

Tone	226 Hz
SA	0.23 mmho
TPP	4 daPa
ECV	0.44 ml
TW	106 daPa
Type	AS

Reflex	Threshold (dB HL)					Decay (s)	
	500	1k	2k	4k	BBN	500	1k
R Ipsi							
L Ipsi							
R Contra							
L Contra							

Probe tone:

PTA (dB HL) / AI (%)

	AC	BC	AI
Right	-2		
Left	110		

Reliability

Good

Speech	SDT		SRT		WRS / SRS 1				WRS / SRS 2				MCL	UCL
	dB HL	[m]	dB HL	[m]	%	dB HL	[m]	S/N	%	dB HL	[m]	S/N	dB HL	dB HL
Right					98	50								
Left					0	110	[70]							
Bin														
Note	1 List 1. 2								2 rec: PBK-50					
Aided														
Note	1								2					

Legend

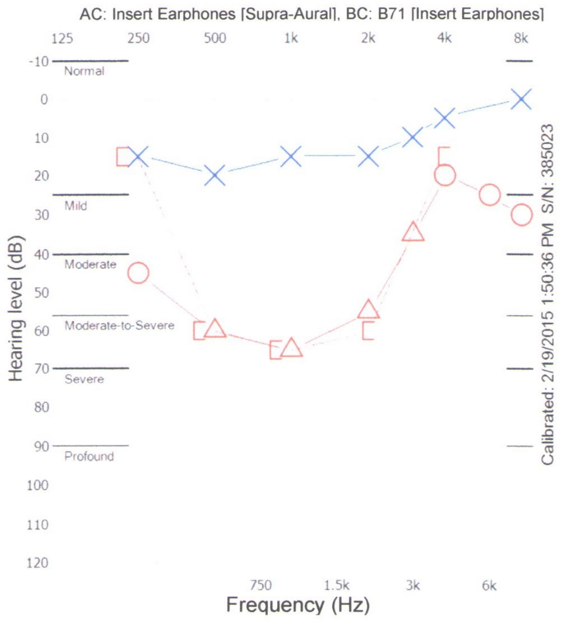
L	R		Masked	
×	○	AC	□	△
>	<	BC	]	[
S	S	SF		
M	M	MCL		
U	U	UCL		
↓	↓	NR		

PTA AC: 500, 1k, 2k
BC: 500, 1k, 2k

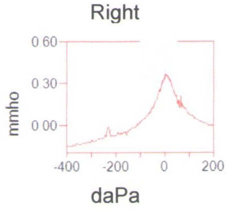
Aud Method: Standard

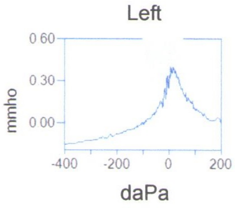
Signed by:

8_U*



AC	R		60	55	45	30		
	L							
BC	R	80	50	50	45		40	
	L							





Tymp

Tone	226 Hz
SA	0.36 mmho
TPP	4 daPa
ECV	0.80 ml
TW	88 daPa
Type	A

Tymp

Tone	226 Hz
SA	0.40 mmho
TPP	16 daPa
ECV	0.82 ml
TW	82 daPa
Type	A

Reflex	Threshold (dB HL)					Decay (s)	
	500	1k	2k	4k	BBN	500	1k
R Ipsi					95		
L Ipsi					85		
R Contra							
L Contra							

Probe tone: 226 Hz

PTA (dB HL) / AI (%)

	AC	BC	AI
Right	60	61	17
Left	16		

Reliability

Good

Speech	SDT		SRT		WRS / SRS 1				WRS / SRS 2				MCL	UCL
	dB HL	[m]	dB HL	[m]	%	dB HL	[m]	S/N	%	dB HL	[m]	S/N	dB HL	dB HL
Right					96	90	[60]							
Left					94	50								
Bin														
Note	[1] rec: PB-K 50								[2] Lists 1 .2					
Aided														
Note	[1]								[2]					

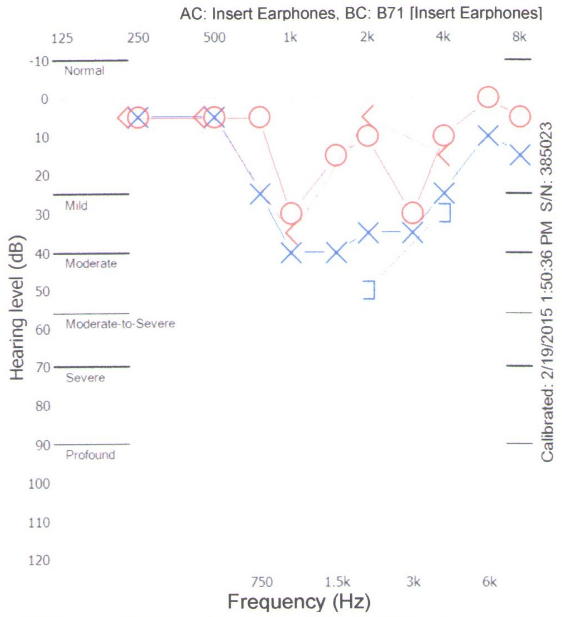
Legend

L		R		Masked	
×		○	AC	□	△
>	^	<	BC	]	[
S	S	S	SF	⊗	∅
M		M	MCL		
U		U	UCL		
↘	↓	↙	NR		

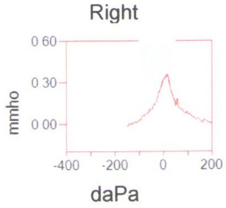
PTA	AC: 500, 1k, 2k BC: 500, 1k, 2k
Aud Method:	Standard

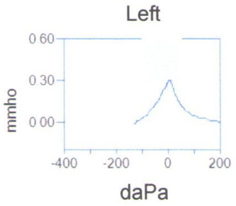
Signed by:

9_U



AC	R		
	L		
BC	R		
	L	40	40





Tymp (Right)

Tone	226 Hz
SA	0.34 mmho
TPP	10 daPa
ECV	0.65 ml
TW	71 daPa
Type	A

Tymp (Left)

Tone	226 Hz
SA	0.29 mmho
TPP	6 daPa
ECV	0.60 ml
TW	83 daPa
Type	AS

Reflex	Threshold (dB HL)					Decay (s)	
	500	1k	2k	4k	BBN	500	1k
R Ipsi							
L Ipsi							
R Contra							
L Contra							

Probe tone:

PTA (dB HL) / AI (%)

	AC	BC	AI
Right	15	15	93
Left	26		64

Reliability

Good

Legend

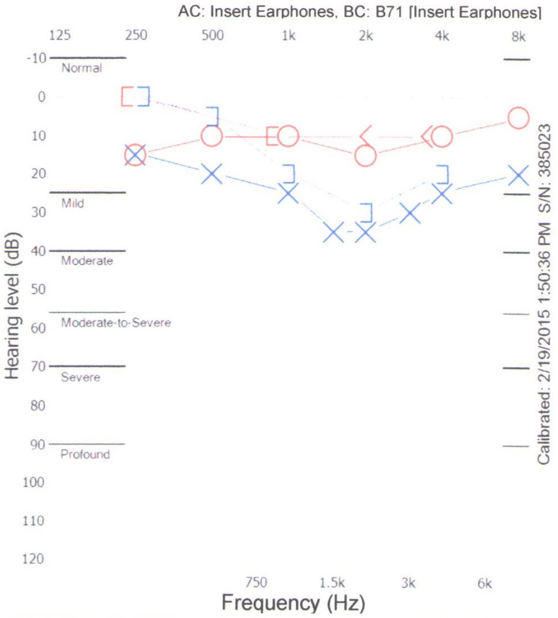
L		R		Masked	
×		○	AC	□	△
>	^	<	BC	]	[
S	S	S	SF	⊠	Ø
M		M	MCL		
U		U	UCL		
↘	↓	↙	NR		

PTA	AC: 500, 1k, 2k BC: 500, 1k, 2k
Aud Method:	Standard

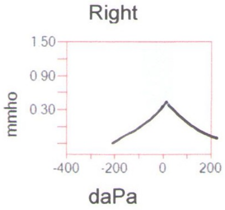
Speech	SDT		SRT		WRS / SRS 1				WRS / SRS 2				MCL	UCL
	dB HL	[m]	dB HL	[m]	%	dB HL	[m]	S/N	%	dB HL	[m]	S/N	dB HL	dB HL
Right					90	50	[20]							
Left					80	70	[40]							
Bin														
Note	[1] Lists 1. 2								[2] rec: CID W-22					
Aided														
Note	[1]								[2]					

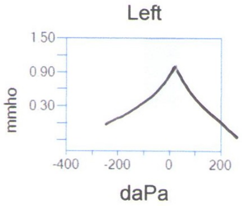
Signed by:

10_U



AC	R					
	L					
BC	R	55		55		
	L	75	75	55	55	45





Tymp (Right)

Tone	226 Hz
SA	0.52 mmho
TPP	10 daPa
ECV	0.98 ml
TW	daPa
Type	A

Tymp (Left)

Tone	226 Hz
SA	1.04 mmho
TPP	30 daPa
ECV	1.77 ml
TW	daPa
Type	A

Reflex	Threshold (dB HL)					Decay (s)	
	500	1k	2k	4k	BBN	500	1k
R Ipsi							
L Ipsi							
R Contra							
L Contra							

Probe tone:

PTA (dB HL) / AI (%)

	AC	BC	AI
Right	11		
Left	26	18	

Reliability

Good

Legend

L		R		Masked	
×		○	AC	□	△
>	^	<	BC	]	[
S	S	S	SF	⊠	∅
M		M	MCL		
U		U	UCL		
↘	↓	↙	NR		

PTA AC: 500, 1k, 2k
BC: 500, 1k, 2k

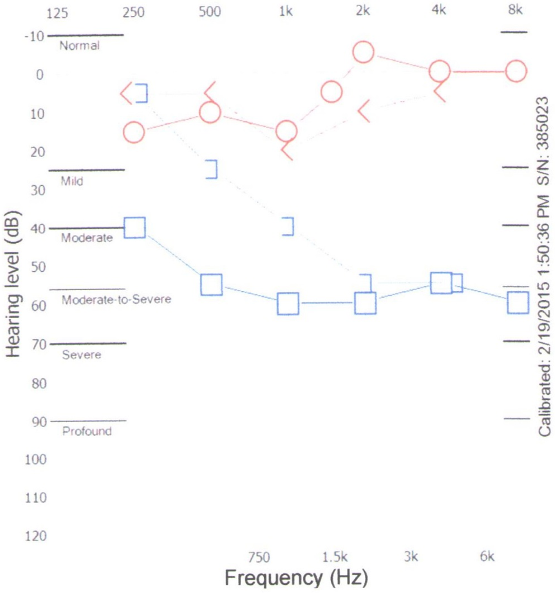
Aud Method: Standard

Signed by:

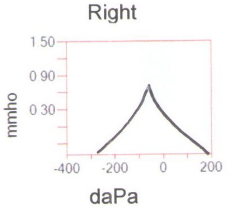
Speech	SDT		SRT		WRS / SRS 1				WRS / SRS 2				MCL	UCL
	dB HL	[m]	dB HL	[m]	%	dB HL	[m]	S/N	%	dB HL	[m]	S/N	dB HL	dB HL
Right					94	50	[20]							
Left					90	65	[35]							
Bin														
Note	[1] rec: CID-W22								[2] Lists 1. 2					
Aided														
Note	[1]								[2]					

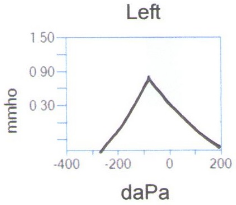
9_HA1

AC: Insert Earphones, BC: B71 [Insert Earphones]



AC	R						
	L	55	40	45	25	30	30
BC	R						
	L	65	50	45	25	30	





Tymp (Right)

Tone	226 Hz
SA	0.67 mmho
TPP	-56 daPa
ECV	1.19 ml
TW	78 daPa
Type	A

Tymp (Left)

Tone	226 Hz
SA	0.87 mmho
TPP	-94 daPa
ECV	1.25 ml
TW	59 daPa
Type	A

Reflex	Threshold (dB HL)					Decay (s)	
	500	1k	2k	4k	BBN	500	1k
R Ipsi							
L Ipsi							
R Contra							
L Contra							

Probe tone:

PTA (dB HL) / AI (%)

	AC	BC	AI
Right	6	11	
Left	58	40	

Reliability

Good

Speech	SDT		SRT		WRS / SRS 1				WRS / SRS 2				MCL	UCL
	dB HL	[m]	dB HL	[m]	%	dB HL	[m]	S/N	%	dB HL	[m]	S/N	dB HL	dB HL
Right					100	50								
Left					70	90	[60]		100	50				
Bin														
Note	[1] Lists 1. 2. 3								[2] rec: CID W-22					
Aided														
Note	1								2					

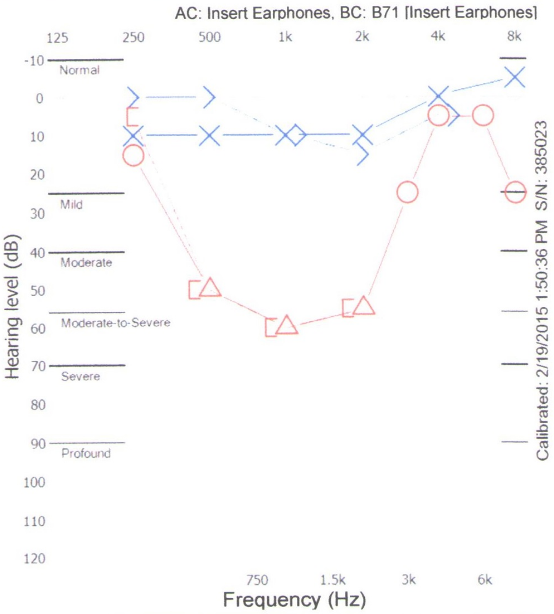
Legend

L		R		Masked	
×		○	AC	□	△
>	^	<	BC	]	[
S	S	S	SF	⊠	∅
M		M	MCL		
U		U	UCL		
↘	↓	↙	NR		

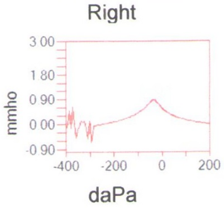
PTA	AC: 500, 1k, 2k BC: 500, 1k, 2k
Aud Method:	Standard

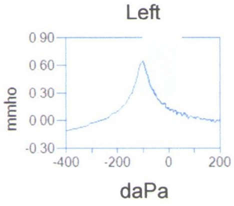
Signed by:

9_HA2*



AC	R		50	40	35
	L				
BC	R	60	50	50	40
	L				





Tymp

Tone	226 Hz
SA	0.88 mmho
TPP	-35 daPa
ECV	1.78 ml
TW	110 daPa
Type	A

Tymp

Tone	226 Hz
SA	0.65 mmho
TPP	-100 daPa
ECV	1.19 ml
TW	81 daPa
Type	A

Reflex	Threshold (dB HL)					Decay (s)	
	500	1k	2k	4k	BBN	500	1k
R Ipsi					~~80~~		
L Ipsi					~~80~~		
R Contra							
L Contra							

Probe tone: 226 Hz

PTA (dB HL) / AI (%)

	AC	BC	AI
Right	55	55	34
Left	10	8	

Reliability

Good

Speech	SDT		SRT		WRS / SRS 1				WRS / SRS 2				MCL	UCL
	dB HL	[m]	dB HL	[m]	%	dB HL	[m]	S/N	%	dB HL	[m]	S/N	dB HL	dB HL
Right					94	85	[55]							
Left					96	50			94	50				
Bin														
Note	1 Lists 1. 2. 3								2 rec: PB-K 50					
Aided														
Note	1								2					

Legend

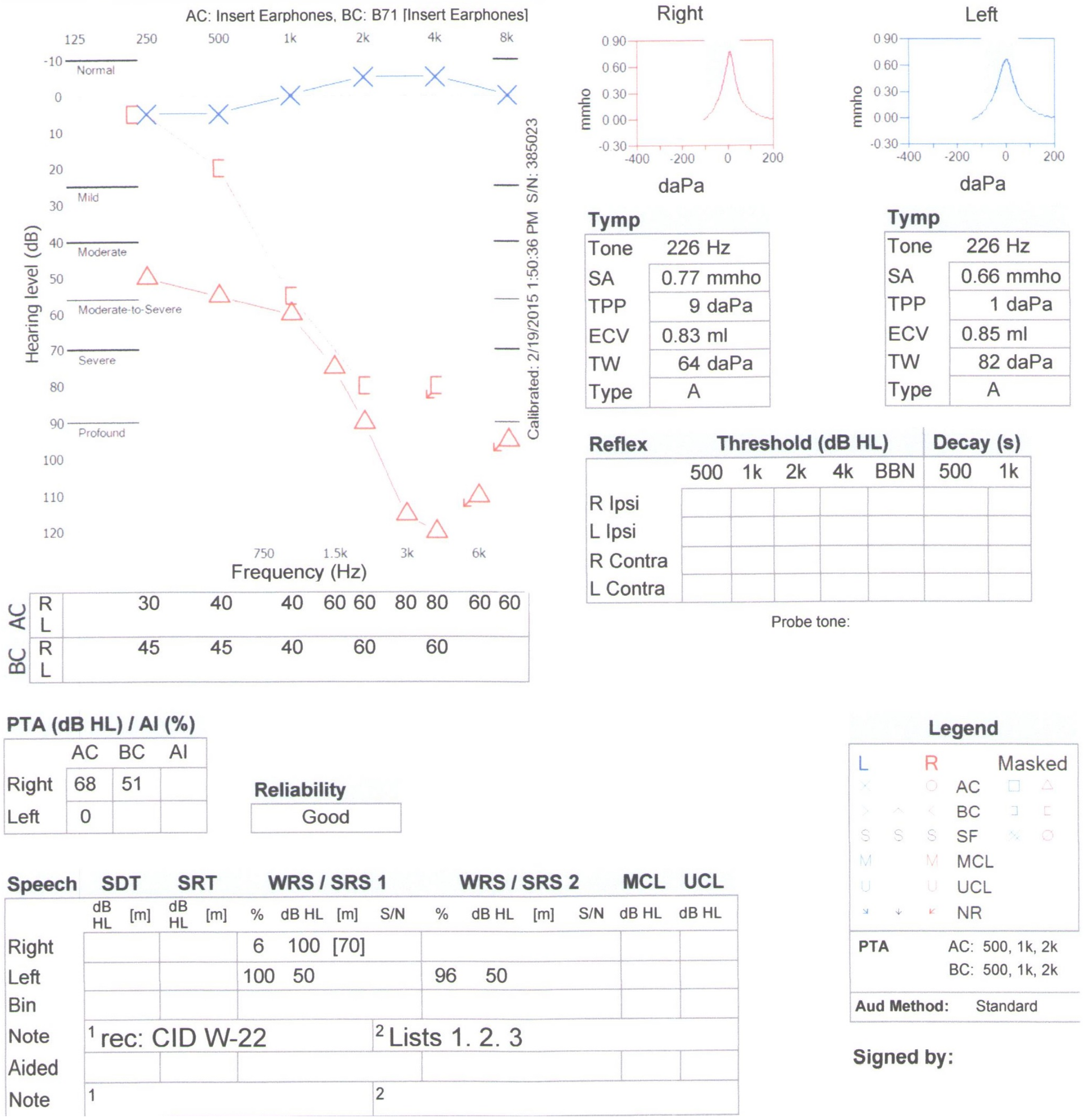
L		R		Masked	
×		○	AC	□	△
>	^	<	BC	]	[
S	S	S	SF	⊠	⌀
M		M	MCL		
U		U	UCL		
↘	↓	↙	NR		

PTA AC: 500, 1k, 2k
BC: 500, 1k, 2k

Aud Method: Standard

Signed by:

11_CROS



AC	R	30	40	40	60	60	80	80	60	60
	L									
BC	R	45	45	40		60		60		
	L									

Tymp (Right)

Tone	226 Hz
SA	0.77 mmho
TPP	9 daPa
ECV	0.83 ml
TW	64 daPa
Type	A

Tymp (Left)

Tone	226 Hz
SA	0.66 mmho
TPP	1 daPa
ECV	0.85 ml
TW	82 daPa
Type	A

Reflex	Threshold (dB HL)					Decay (s)	
	500	1k	2k	4k	BBN	500	1k
R Ipsi							
L Ipsi							
R Contra							
L Contra							

Probe tone:

PTA (dB HL) / AI (%)

	AC	BC	AI
Right	68	51	
Left	0		

Reliability

Good

Speech	SDT		SRT		WRS / SRS 1				WRS / SRS 2				MCL	UCL
	dB HL	[m]	dB HL	[m]	%	dB HL	[m]	S/N	%	dB HL	[m]	S/N	dB HL	dB HL
Right					6	100	[70]							
Left					100	50			96	50				
Bin														
Note	[1] rec: CID W-22								[2] Lists 1. 2. 3					
Aided														
Note	[1]								[2]					

Legend

L		R		Masked	
×		○	AC	□	△
>	^	<	BC	]	[
S	S	S	SF	⊗	⊘
M		M	MCL		
U		U	UCL		
↘	↓	↙	NR		

PTA AC: 500, 1k, 2k
BC: 500, 1k, 2k

Aud Method: Standard

Signed by:

APPENDIX D

TEST SITES

Primary Test Site:

The Center for Language, Speech, and Hearing
University of Massachusetts Amherst
358 North Pleasant Street
Amherst, MA 01003-9296

Equipment Specifications:

- Sound-treated booth
  - Model: IAC-102768
  - Dimensions (length x width x height): 8’7” x 7’4” x 8’
  - Reverberation Time (wideband T_{60}): 49.3 ms
- Audiometer
  - Model: Grason-Stadler Instruments (GSI) 61 Clinical Audiometer
  - Circum-aural Headphones: Telephonics TDH-50P
  - Insert earphones: EARTone 3A Insert Earphones
- Impedance Bridge
  - Model: GSI 33 Middle-Ear Analyzer
- Hearing Aid Verification System
  - Model: Audioscan Verifit

Secondary Test Site:

Audiology Department
University of Massachusetts Memorial Medical Center
55 Lake Avenue North
Worcester, MA 01655

- Sound-treated booth
  - Model: Eckel C-16 Mod Rev
  - Dimensions (length x width x height): 11’ 3” x 6’ 3” x 6’ 5.5”
  - Reverberation Time (wideband T_{60}): 55.1 ms
- Audiometer
  - Model: Otometrics Madsen Astera
  - Circum-aural Headphones: Telephonics TDH-39
  - Insert earphones: E.A.RTone 3A
- Impedance Bridge
  - Model: Otometrics Otoflex 100
- Hearing Aid Verification System

Model: Audioscan Verifit

APPENDIX E

LOUDSPEAKER SPECIFICATIONS

General specifications MSP3

Speaker type		2-way powered speaker
Frequency response	**-10dB**	65Hz-22kHz
Components	**LF**	4" (10cm) cone
	HF	1/8" (2.2cm) dome
Output power		20W
I/O connectors		Line 1: -10dB (RCA-pin), Line 2: +4dB (XLR3-31 type, Phone)
Power consumption		30W
Magnetic shielding		Yes
Dimensions	**W**	144mm; 5-5/8in
	H	236mm; 9-1/4in
	D	167mm; 6-5/8in
Net weight		4.4kg; 9.7lbs

APPENDIX F

WORD LISTS

Phonetically Balanced Kindergarten (PBK) lists (Haskins, 1949)

LIST 1		**LIST 2**	
1. PLEASE	26. SMILE	1. LAUGH	26. PATH
2. GREAT	27. BATH	2. FALLS	27. FEED
3. SLED	28. SLIP	3. PASTE	28. NEXT
4. PANTS	29. RIDE	4. PLOW	29. WRECK
5. RAT	30. END	5. PAGE	30. WASTE
6. BAD	31. PINK	6. WEED	31. CRAB
7. PINCH	32. THANK	7. GRAY	32. PEG
8. SUCH	33. TAKE	8. PARK	33. FREEZE
9. BUS	34. CART	9. WAIT	34. RACE
10. NEED	35. SCAB	10. FAT	35. BUD
11. WAYS	36. LAY	11. AX	36. DARN
12. FIVE	37. CLASS	12. CAGE	37. FAIR
13. MOUTH	38. ME	13. KNIFE	38. SACK
14. RAG	39. DISH	14. TURN	39. GOT
15. PUT	40. NECK	15. GRAB	40. AS
16. FED	41. BEEF	16. ROSE	41. GREW
17. FOLD	42. FEW	17. LIP	42. KNEE
18. HUNT	43. USE	18. BEE	43. FRESH
19. NO	44. DID	19. BET	44. TRAY
20. BOX	45. HIT	20. HIS	45. CAT
21. ARE	46. POND	21. SING	46. ON
22. TEACH	47. POT	22. ALL	47. CAMP
23. SLICE	48. OWN	23. BLESS	48. FIND
24. IS	49. BEAD	24. SUIT	49. YES
25. TREE	50. SHOP	25. SPLASH	50. LOUD

Central Institute for the Deaf W-22 Word Lists

	List 1A	List 2A
1	an	yore
2	yard	bin
3	carve	way
4	us	chest
5	day	then
6	toe	ease
7	felt	smart
8	stove	gave
9	hunt	pew
10	ran	ice
11	knees	odd
12	not	knee
13	mew	move
14	low	now
15	owl	jaw
16	it	one
17	she	hit
18	high	send
19	there	else
20	earn	tear
21	twins	does
22	could	too
23	what	cap
24	bathe	with
25	ace	air
26	you	and
27	as	young
28	wet	cars
29	chew	tree
30	see	dumb
31	deaf	that
32	them	die
33	give	show
34	true	hurt
35	isle	own
36	or	key
37	law	oak
38	me	new
39	none	live
40	jam	off
41	poor	ill
42	him	rooms
43	skin	ham
44	east	star
45	thing	eat
46	dad	thin
47	up	flat
48	bells	well
49	wire	by
50	ache	ail

APPENDIX G

PARENT QUESTIONNAIRE

ID # ________________ DATE __________

PARENT QUESTIONNAIRE- NH

SECTION 1: FAMILY HISTORY

What is your child's birthdate?	
What is your child's age?	
What is your child's sex?	*Circle one.* Male Female
What is your child's handedness?	*Circle one.* Right Left Both equally well
What is your child's race?	*Circle all that apply.* American Indian or Alaskan Native Asian Black or African American Native Hawaiian or Other Pacific Islander White Other
What is(are) your child's first language(s)?	
Does your child know more than one language? If so, please list.	
What is your child's town and state of residence?	
What is the name of the school your child attends?	
What grade is your child in?	
What is the highest education level of your child's mother?	
What is your child's current medical insurance?	
What is the marital status of your child's parental guardians?	

ID # ________________   DATE __________

SECTION 2: HEARING HISTORY

Did your child pass his/her newborn hearing screening?	*Circle one.* Pass Refer I don't know
Has your child ever had any ear surgeries? If so, please describe.	*Circle one.* Yes No
Does your child have a history of middle ear infections? If so, how was he/she treated?	*Circle one.* Yes No

ID # ________________ DATE __________

SECTION 3: DEVELOPMENTAL HISTORY

Was your baby born full term or prematurely? If your baby was born prematurely, how many weeks early did he/she arrive?	*Circle one.* Full term Premature *(<37 weeks)*
Did your child receive any medical treatments following his/her birth, while still in the hospital? If so, what kinds of treatments did he/she receive?	*Circle one.* Yes No
Did your child receive Early Intervention (EI) Services before 3 years of age? If so, what type of services and with what frequency? *For example: Speech-language therapy 4 per month*	*Circle one.* Yes No
Has your child ever been diagnosed with a developmental delay? If so, in what developmental areas? *For example: Speech and Language, Motor, Social, or Cognitive*	*Circle one.* Yes No
Does your child have any medical or mental health diagnoses?	

ID # ________________ DATE __________

SECTION 4: ACADEMIC HISTORY

How would you describe your child's current academic status?	*Circle one.* Above average Average Below average
Which subject(s) does your child excel at?	
Which subject(s) does your child need improvement in?	
Has your child ever repeated a grade?	*Circle one.* Yes No
What types of comments does your child's teacher make about his/her performance in school?	
Has your child received special educational services? If so, please circle the plan type and list what kinds of services they receive? *For example: Speech-language therapy 1 x week*	*Circle one.* Yes No *Circle One:* 504 Plan IEP DCAP
Do you have any concerns regarding your child's academic performance? If so, please describe.	*Circle one.* Yes No

ID # ________________ DATE __________

PARENT QUESTIONNAIRE- UHL

SECTION 1: FAMILY HISTORY

What is your child's birthdate?	
What is your child's age?	
What is your child's sex?	*Circle one.* Male Female
What is your child's handedness?	*Circle one.* Right Left Both equally well
What is your child's race?	*Circle all that apply.* American Indian or Alaskan Native Asian Black or African American Native Hawaiian or Other Pacific Islander White Other
What is(are) your child's first language (s)?	
Does your child know more than one language? If so, please list.	
What is your child's town and state of residence?	
What is the name of the school your child attends?	
What grade is your child in?	
What is the highest education level of your child's mother?	
What is your child's current medical insurance?	
What is the marital status of your child's parental guardians?	

ID # ________________ DATE __________

SECTION 2: HEARING HISTORY

Did your child pass his/her newborn hearing screening?	*Circle one.* Pass Refer I don't know
At what age was your child diagnosed with permanent hearing loss?	*Please report in months.*
Has your child ever received any imaging studies (e.g., MRI, CT-scan) of the auditory system?	
Has the cause of your child's hearing loss been identified?	
On what side does your child have hearing loss?	*Circle one.* Right Left Both
What degree of hearing loss does your child have?	*Circle all that apply.* Mild Moderate Moderately-severe Severe Profound I don't know
What type of hearing loss does your child have?	*Circle one.* Sensorineural Conductive Mixed I don't know
Following diagnosis of your child's hearing loss, was a hearing aid or assistive listening device recommended? If so, at what age did your child start wearing his/her hearing device?	*Circle one.* Yes No *Please report in months.*

ID # ________________ DATE __________

SECTION 2: HEARING HISTORY CONTINUED

What type of hearing devices has your child trialed?	*Circle all devices that have been trialed.* Traditional hearing aid CROS hearing aid system Osseointegrated implantable hearing device (Baha) FM system None I don't know
What type of hearing devices does your child currently use?	*Circle all devices that are currently being used.* Traditional hearing aid CROS hearing aid system Osseointegrated implantable hearing device (Baha) FM system None
How long has your child used his/her current hearing device?	*Report in months.*
How often does your child wear his/her hearing device?	Days per week = _________ Hours per day = __________
Has your child ever had any ear surgeries? If so, please describe.	*Circle one.* Yes No
Does your child have a history of middle ear infections? If so, how was he/she treated?	*Circle one.* Yes No

ID # ________________ DATE __________

SECTION 3: DEVELOPMENTAL HISTORY

Was your baby born full term or prematurely? If your baby was born prematurely, how many weeks early did he/she arrive?	*Circle one.* Full term Premature *(<37 weeks)*
Did your child receive any medical treatments following his/her birth, while still in the hospital? If so, what kinds of treatments did he/she receive?	*Circle one.* Yes No
Did your child receive Early Intervention (EI) Services before 3 years of age? If so, what type of services and with what frequency? *For example: Speech-language therapy 4 per month*	*Circle one.* Yes No
Has your child ever been diagnosed with a developmental delay? If so, in what developmental areas? *For example: Speech and Language, Motor, Social, or Cognitive*	*Circle one.* Yes No
Does your child have any medical or mental health diagnoses?	

ID # ________________ DATE __________

SECTION 4: ACADEMIC HISTORY

How would you describe your child's current academic status?	*Circle one.* Above average Average Below average
Which subject(s) does your child excel at?	
Which subject(s) does your child need improvement in?	
Has your child ever repeated a grade?	*Circle one.* Yes No
What types of comments does your child's teacher make about his/her performance in school?	
Has your child received special educational services? If so, please circle the plan type and list what kinds of services they receive? *For example: Speech-language therapy 1 x week*	*Circle one.* Yes No *Circle One:* 504 Plan IEP DCAP
Does an audiologist provide services to your child at school? If so, what does he/she do for your child?	*Circle one.* Yes No I don't know.
Do you have any concerns regarding your child's academic performance? If so, please describe.	*Circle one.* Yes No

APPENDIX H

COVER LETTER TO CLASSROOM TEAHCERS

UNIVERSITY OF MASSACHUSETTS
AMHERST

Communication Disorders
358 North Pleasant Street
Amherst, MA 01003-9296

SAMPLE COVER LETTER TO SUBJECT'S TEACHERS

Dear CLASSROOM TEACHER,

A student in your class, NAME, has taken part in a study examining the impact of congenital, unilateral hearing loss on speech perception and comprehension. As part of the study we are very interested in better understanding NAME's current academic status. NAME's parent has provided his/her written consent for me to contact you with the following request.

Attached you will find a very brief questionnaire, named the Screening Instrument for Targeting Educational Risk (SIFTER). The SIFTER is a 15-item teacher questionnaire, which uses a simple 5-point scale. You will be asked to rate STUDENT on their academic ability, attention, communication skills, class participation, and school behavior.

Your willingness to complete this questionnaire to the best of your ability is greatly appreciated. Please use the self addressed stamped envelope provided to mail the completed form back to me.

If you prefer you may also electronically attach the completed document in an email addressed to me at amgriffi@comdis.umass.edu.

Thank you in advance for your time and knowledge on this matter.

Sincerely,

Amanda Griffin
Ph.D. Candidate, Clinical Audiology
University of Massachusetts, Amherst

APPENDIX I

SIFTER QUESTIONNAIRE

S.I.F.T.E.R.

SCREENING INSTRUMENT FOR TARGETING EDUCATIONAL RISK

by Karen L. Anderson, Ed.S., CCC-A

STUDENT __________________________________ TEACHER ___________________ GRADE _________

DATE COMPLETED ____________ SCHOOL ______________________________ DISTRICT ___________

The above child is suspect for hearing problems which may or may not be affecting his/her school performance.
This rating scale has been designed to sift out students who are educationally at risk possibly as a result of hearing problems.
Based on your knowledge from observations of this student, circle the number best representing his/her behavior.
After answering the questions, please record any comments about the student in the space provided on the reverse side.

1. What is your estimate of the student's class standing in comparison of that of his/her classmates?	UPPER 5	4	MIDDLE 3	2	LOWER 1	ACADEMICS	☐
2. How does the student's achievement compare to your estimation of her/her potential?	EQUAL 5	4	LOWER 3	2	MUCH LOWER 1		
3. What is the student's reading level, reading ability group or reading readiness group in the classroom (e.g., a student with average reading ability performs in the middle group)?	UPPER 5	4	MIDDLE 3	2	LOWER 1		
4. How distractible is the student in comparison to his/her classmates?	NOT VERY 5	4	AVERAGE 3	2	VERY 1	ATTENTION	☐
5. What is the student's attention span in comparison to that of his/her classmates?	LONGER 5	4	AVERAGE 3	2	SHORTER 1		
6. How often does the student hesitate or become confused when responding to oral directions (e.g., "Turn to page . . .")?	NEVER 5	4	OCCASIONALLY 3	2	FREQUENTLY 1		
7. How does the student's comprehension compare to the average understanding ability of her/her classmates?	ABOVE 5	4	AVERAGE 3	2	BELOW 1	COMMUNICATION	☐
8. How does the student's vocabulary and word usage skills compare with those of other student s in his/her age group?	ABOVE 5	4	AVERAGE 3	2	BELOW 1		
9. How proficient is the student at telling a story or relating happenings from home when compared to classmates?	ABOVE 5	4	AVERAGE 3	2	BELOW 1		
10. How often does the student volunteer information to class discussions or in answer to teacher questions?	FREQUENTLY 5	4	OCCASIONALLY 3	2	NEVER 1	CLASS PARTICIPATION	☐
11. With what frequency does the student complete his/her class and homework assignments within the time allocated?	ALWAYS 5	4	USUALLY 3	2	SELDOM 1		
12. After instruction, does the student have difficulty starting to work (looks at other students working or asks for help)?	NEVER 5	4	OCCASIONALLY 3	2	FREQUENTLY 1		
13. Does the student demonstrate any behaviors that seem unusual or inappropriate when compared to other students?	NEVER 5	4	OCCASIONALLY 3	2	FREQUENTLY 1	SCHOOL BEHAVIOR	☐
14. Does the student become frustrated easily, sometimes to the point of losing emotional control?	NEVER 5	4	OCCASIONALLY 3	2	FREQUENTLY 1		
15. In general, how would you rank the student's relationship with peers (ability to get along with others)?	GOOD 5	4	AVERAGE 3	2	POOR 1		

TEACHER COMMENTS

Has this child repeated a grade, had frequent absences or experienced health problems (including ear infections and colds)? Has the student received, or is he/she now receiving, special services? Does the child have any other health problems that may be pertinent to his/her educational functioning?

The S.I.F.T.E.R. is a SCREENING TOOL ONLY

Any student failing this screening in a content area as determined on the scoring grid below should be considered for further assessment, depending on his/her individual needs as per school district criteria. For example, failing in the Academics area suggests an educational assessment, in the Communication area a speech-language assessment, and in the School Behavior area an assessment by a psychologist or a social worker. Failing in the Attention and/or Class Participation area in combination with other areas may suggest an evaluation by an educational audiologist. Children placed in the marginal area are at risk for failing and should be monitored or considered for assessment depending upon additional information.

SCORING

Sum the responses to the three questions in each content area and record in the appropriate box on the reverse side and under Total Score below. Place an **X** on the number that corresponds most closely with the content area score (e.g., if a teacher circled 3, 4 and 2 for the questions in the Academics area, an X would be placed on the number 9 across from the Academics content area). Connect the **X**'s to make a profile.

CONTENT AREA	TOTAL SCORE	PASS	MARGINAL	FAIL
ACADEMICS		15 14 13 12 11 10	9 8	7 6 5 4 3
ATTENTION		15 14 13 12 11 10 9	8 7	6 5 4 3
COMMUNICATION		15 14 13 12 11	10 9 8	7 6 5 4 3
CLASS PARTICIPATION		15 14 13 12 11 10 9	8 7	6 5 4 3
SOCIAL BEHAVIOR		15 14 13 12 11 10	9 8	7 6 5 4 3

APPENDIX J

REAL-EAR MEASUREMENTS FOR UHL-A SUBJECTS

HA1	Frequency (Hz)								
	250	**500**	**750**	**1000**	**1500**	**2000**	**3000**	**4000**	**6000**
Target 1 (50 dB SPL input)	67	74	75	75	77	83	82	78	76
Curve 1: REAG	49	66	69	74	77	82	82	78	74
Target 2 (90 dB SPL input)	74	83	88	88	92	97	97	93	86
Curve 2: REAG	56	76	84	90	93	100	99	87	92
Target 3 (65 dB SPL input)	71	79	82	81	84	90	90	86	81
Curve 3: REAG	54	71	76	82	84	91	90	77	83

HA2	Frequency (Hz)								
	250	**500**	**750**	**1000**	**1500**	**2000**	**3000**	**4000**	**6000**
Target 1 (50 dB SPL input)	76	80	79	76	75	76	72	67	69
Curve 1: REAG	64	73	74	76	76	75	67	69	61
Target 2 (90 dB SPL input)	81	89	91	88	90	92	89	85	81
Curve 2: REAG	67	78	85	87	90	91	83	86	77
Target 3 (65 dB SPL input)	79	85	85	82	82	83	80	76	75
Curve 3: REAG	67	76	80	81	81	82	73	75	68

11_CROS	Frequency (Hz)								
	250	**500**	**750**	**1000**	**1500**	**2000**	**3000**	**4000**	**6000**
Curve 1: REUG	44	45	46	46	48	55	58	57	50
Curve 2: REIG	46	46	45	45	45	57	64	62	54

Legend Key

REAG = real-ear aided gain
REUG = real-ear unaided gain
REIG = real-ear insertion gain

APPENDIX K

EXPERIMENT 1 - INSTRUCTIONS TO SUBJECTS

“Now you are going to listen to sentences read by a man. Listen carefully, because after each sentence I will ask you to repeat everything you heard. Sometimes you will also hear static noise or other people talking in the background. Ignore those sounds and only listen to the man saying the sentences. His voice will always come from the loudspeaker directly in front of you. Sometimes the sentences will be repeated, a little bit louder each time. You will not be able to understand all of the sentences every time- that’s okay. Do not be discouraged, I just ask that you try your best. If you aren’t sure what he said, always just take a guess. Do you have any questions?”

APPENDIX L

TEST OF NARRATIVE LANGUAGE (TNL) STORIES AND QUESTIONS

McDonald's

On Tuesday, when Lisa and Raymond got home from school, their mother said, "Tonight we're going out to eat. Where do you want to go?" Lisa and Raymond both yelled, "McDonald's!" They jumped into the car and their mother drove them to the nearest McDonald's. As they walked into the restaurant, Lisa said she couldn't decide whether to get a Big Mac or a Happy Meal. Raymond and their mother both knew what they wanted. When they got to the counter, Raymond asked for a cheeseburger, French fries, and a large vanilla milk shake. Their mother ordered a salad. Lisa finally made up her mind. She told the clerk, I'll have a Happy Meal, a Coke, and a chocolate ice cream cone." The clerk said, "That will be twelve dollars and fifty cents," When their mother reached for her purse, it wasn't there. She realized she had left it on the kitchen counter at home.

155 words
Duration: 0.57.954 minutes

McDonald's Questions:

1. What should they do?
2. What was the girl's name?
3. What was the boy's name?
4. Was anyone else in the story?
5. Where were the children when they talked to their mother about eating out?
6. Where did they eat?
7. What kind of a milk shake did Raymond want?
8. What did their mother order?
9. What did Lisa order?
10. What kind of ice cream cone did she want?
11. What was the problem in the story?

The Shipwreck

Last week, Samantha's class was studying the ocean. Each child was supposed to turn in an art project that had something to do with the ocean. Samantha decided to build a ship, and her mother helped. Samantha and her mother worked on the ship for three days. On the day Samantha took her ship to school her mother said, "That sure is a great-looking ship. I'll be you get an A!" As Samantha was walking to school, she accidentally tripped on a rock. She dropped her ship in to a mud puddle. Her ship was ruined and she felt terrible. She started to cry, but then she thought, "I'm not going to cry about this. I'll just have to take my ship to school and fix it." When Samantha got to school, she got busy putting her ship back together. It wasn't as good as it once was, but it was certainly better than nothing. When her teacher came over, she was surprised to see a muddy, half-broken ship. After Samantha told her what happened, her teacher said, "Samantha, you deserve an A+ for the way you handled that problem.

190 words
Duration: 1.07.723 minutes

The Shipwreck Story Questions

1. What was the girl's name?
2. Who else was in the story?
3. What was Samantha's class studying?
4. Where did Samantha build the ship?
5. What was the problem in the story?
6. How did Samantha feel when her ship fell in the mud?
7. Why did she feel that way?
8. What did Samantha decide to do with her ship after it fell in the mud?
9. What grade did the teacher give Samantha?

The Dragon

One Saturday morning, Daniel and Michelle found a new trail they had never seen before. They decided to follow it to see where it led. As they came around a bend, they heard a strange hissing sound. Daniel snuck up behind a large rock and peeked over. He whispered to Michelle, "I can't believe it! I think there's a dragon by the cave over there." Michelle peeked over the rock to see for herself. She was excited! She ducked down and said, "Yep, that's a dragon all right, and he's guarding a treasure chest!" Daniel was scared. He said, "Let's go tell Mom and Dad what we found." He started to get up and run off. Michelle grabbed his arm and said, "Wait. Nobody will ever believe us. We need to take a piece of gold back with us as proof. Then they'll know we're telling the truth." Daniel thought this was a really bad idea. He said, "If the dragon catches us, we'll be cooked." Just then, they heard the dragon going back into the cave. Michelle said, "Now's our chance," and then she dashed around the rock. She ran up to the treasure chest and started grabbing all the gold and jewelry she could get her hands on. The dragon heard her, dashed out from the cave, and blew blazes of fire out of his mouth. Seeing the flames fly toward her, Michelle screamed with fear, dropped all the treasure she had taken, and ran as fast as she could, right past Daniel. Daniel, his eyes wide in terror, followed as fast his legs would carry him. They didn't stop running, until they reached the end of the trail. After they caught their breath, Daniel and Michelle went home and told their parents about their adventure. They didn't have any treasure to prove their story was true. Their father said, "I find this pretty hard to believe." "We can prove it," Daniel and Michelle yelled, "We'll take you back to the trail." The family walked to the place where Daniel and Michelle thought the trail began. They looked and looked for the trail, but they never found it. To this day, Michelle and Daniel are not sure if their experience with the dragon was real or just a dream.

381 words
Duration: 2.28.922

The Dragon Questions:

1. What were the children's names?
2. Where were they walking before they saw the dragon?
3. What did Michelle want to take back with them?
4. What did Daniel think about Michelle's plan to take a piece of gold?
5. What were the problems in the story?
6. What did Michelle do after the dragon blew fire at her?
7. Where did Daniel and Michelle go after they were scared?
8. What did Daniel and Michelle do when they got home?
9. What did their father say?
10. What did the family do?

Practice Story: Rudy and Louis

Taken from the CELF-5 Understanding Spoken Paragraphs; Test Paragraphs for ages 5-6

It had been raining for two days, and the twins were tired of playing indoors. They wished it would stop raining. Rudy wanted to play baseball. Louis wanted to play on the new swings at the playground, and then play baseball with his brother Rudy. As they got ready for bed that night, they could still hear the rain coming down on the roof. When they woke up the next morning, they didn't hear the rain. Instead, Rudy and Louis heard birds chirping outside their window.

Practice Questions:

Q1: Why did Rudy and Louis wish it would stop raining?
Q2: What did Rudy and Louis hear before they went to bed?

APPENDIX M

EXPERIMENT 2 - INSTRUCTIONS TO SUBJECTS

"Now you are going to listen to some short stories read by a woman. Listen carefully, because after each story I'll ask you some questions about them. In some of the stories you will hear other people talking the background. You should try to ignore these talkers and just focus on the woman talking to you. Her voice will always come from the speaker directly in front of you. Do you have any questions?"

APPENDIX N

ORDER OF EVENTS FOR TEST SESSIONS

1. Obtain subject assent and parental consent

2. Routine hearing test:
    - Otoscopic check
    - Tympanometry
    - Pure-tone audiometry
    - Word recognition testing in quiet

    For hearing-impaired subjects using a hearing device only:
    - Listening check of hearing device followed by real-ear measurements
    - Word recognition in quiet with device on (speech presented in the sound field at 65 dBA/50 dB HL)

3. 1st subject break. Guardian was given the parent questionnaire to complete independently.

4. Experiment 1
    - Practice list
    - Quiet condition
    - 1st set of 7 noisy conditions

5. 2nd break

6. Experiment 1 continued
    - 2nd set of 7 noisy conditions

7. 3rd break

8. Experiment 2

9. 4th break

10. Administer the CELF-5 screening test

11. Administer the HEAR-QL

At this point, pediatric subjects had completed their participation in the study.

12. Review completed parent questionnaire.

13. Give parent SIFTER questionnaire to pass along to subject’s classroom teacher.

APPENDIX O

INDIVIDUAL AND MEAN RTS DATA FOR NH ADULT SUBJECTS

			Front/ Front		Front/ Impaired (Right)		Front/ Normal (Left)		Front/ Side		Front/ Impaired & Normal
Subject Code	Age (years)	Quiet	TTB	SSN	TTB	SSN	TTB	SSN	TTB	SSN	TTB
NH_A_1	21	7.43	-9.86	-5.29	-17.14	-7.43	-18.00	-8.57	-17.57	-8.00	-13.43
NH_A_2	19	12.29	-10.57	-2.14	-14.43	-7.43	-14.71	-10.00	-14.57	-8.71	-12.00
NH_A_3	20	12.57	-9.14	-1.86	-14.29	-7.57	-13.86	-7.57	-14.07	-7.57	-10.57
NH_A_4	20	8.00	-8.71	-1.57	-14.14	-8.71	-13.00	-9.29	-13.57	-9.00	-10.29
NH_A_6	20	10.29	-10.29	-2.57	-15.43	-7.29	-16.86	-10.00	-16.14	-8.64	-9.14
NH_A_7	20	20.86	-9.14	-2.43	-12.00	-7.71	-13.14	-10.71	-12.57	-9.21	-10.86
NH_A_8	19	12.57	-9.29	-4.86	-14.29	-8.57	-17.71	-10.29	-16.00	-9.43	-12.29
NH_A_9	21	8.00	-8.14	-4.00	-16.57	-7.29	-15.71	-9.29	-16.14	-8.29	-13.43
NH_A_10	19	9.71	-9.86	-4.57	-14.14	-7.71	-15.29	-10.57	-14.71	-9.14	-13.57
NH_A_12	20	12.86	-7.43	-2.14	-13.86	-6.57	-18.00	-9.00	-15.93	-7.79	-12.57
NH_A_13	20	18.86	-9.14	-4.14	-14.43	-7.43	-15.14	-9.00	-14.79	-8.21	-10.00
NH_A_14	19	7.43	-6.14	-3.71	-10.57	-7.71	-13.43	-8.29	-12.00	-8.00	-10.14
NH_A_15	20	10.29	-12.00	-3.14	-13.71	-8.14	-14.43	-7.00	-14.07	-7.57	-8.57
NH_A_16	20	9.43	-8.86	-3.71	-16.14	-8.00	-17.43	-10.43	-16.79	-9.21	-13.71
NH_A_17	23	12.00	-10.71	-1.71	-0.57	-8.71	-15.86	-10.14	-8.21	-9.43	-10.86
NH_A_19	28	9.14	-9.14	-2.14	-16.43	-8.00	-15.43	-7.86	-15.93	-7.93	-11.14
NH_A_20	20	13.71	-8.57	-3.00	-11.14	-7.29	-13.57	-6.86	-12.36	-7.07	-8.71
NH_A_21	23	8.86	-8.57	-3.00	-11.29	-9.71	-15.29	-8.57	-13.29	-9.14	-11.00
MEAN		11.35	-9.20	-3.11	-13.37	-7.85	-15.38	-9.08	-14.37	-8.46	-11.24

APPENDIX P

INDIVIDUAL AND MEAN SRM DATA FOR NH ADULT SUBJECTS

		Front/ Impaired (Right)		Front/ Normal (Left)		Front/ Side		Front/ Impaired & Normal
Subject Code	Age (years)	TTB	SSN	TTB	SSN	TTB	SSN	TTB
NH_A_1	21	7.29	2.14	8.14	3.29	7.71	2.71	3.57
NH_A_2	19	3.86	5.29	4.14	7.86	4.00	6.57	1.43
NH_A_3	20	5.14	5.71	4.71	5.71	4.93	5.71	1.43
NH_A_4	20	5.43	7.14	4.29	7.71	4.86	7.43	1.57
NH_A_6	20	5.14	4.71	6.57	7.43	5.86	6.07	-1.14
NH_A_7	20	2.86	5.29	4.00	8.29	3.43	6.79	1.71
NH_A_8	19	5.00	3.71	8.43	5.43	6.71	4.57	3.00
NH_A_9	21	8.43	3.29	7.57	5.29	8.00	4.29	5.29
NH_A_10	19	4.29	3.14	5.43	6.00	4.86	4.57	3.71
NH_A_12	20	6.43	4.43	10.57	6.86	8.50	5.64	5.14
NH_A_13	20	5.29	3.29	6.00	4.86	5.64	4.07	0.86
NH_A_14	19	4.43	4.00	7.29	4.57	5.86	4.29	4.00
NH_A_15	20	1.71	5.00	2.43	3.86	2.07	4.43	-3.43
NH_A_16	20	7.29	4.29	8.57	6.71	7.93	5.50	4.86
NH_A_17	23	-10.14	7.00	5.14	8.43	-2.50	7.71	0.14
NH_A_19	28	7.29	5.86	6.29	5.71	6.79	5.79	2.00
NH_A_20	20	2.57	4.29	5.00	3.86	3.79	4.07	0.14
NH_A_21	23	2.71	6.71	6.71	5.57	4.71	6.14	2.43
MEAN		4.17	4.74	6.18	5.97	5.17	5.35	2.04

APPENDIX Q

INDIVIDUAL RTS DATA FOR NH PEDIATRIC SUBJECTS

				Front/ Front		Front/ Impaired (Right)		Front/ Normal (Left)		Front/ Side		Front/ Impaired & Normal
Subject Code	Age (years)	Age (months)	Quiet	TTB	SSN	TTB	SSN	TTB	SSN	TTB	SSN	TTB
NH_31	6	72	21.71	-1.57	-0.71	-4.14	-3.29	-8.29	-5.57	-6.21	-4.43	-1.14
NH_39	6	72	20.00	-1.71	-1.00	-2.57	-4.57	-6.14	-1.57	-4.36	-3.07	-4.71
NH_06	6	74	18.86	-1.57	-0.29	-7.43	-3.57	-8.71	-6.14	-8.07	-4.86	-7.29
NH_09	6	80	21.71	-1.00	0.71	-5.71	-1.57	-5.14	-3.14	-5.43	-2.36	-4.71
NH_21	6	80	16.00	-3.57	-2.43	-11.86	-7.00	-8.86	-7.71	-10.36	-7.36	-9.29
NH_05	7	84	11.14	-7.00	-1.71	-17.29	-6.57	-12.43	-9.57	-14.86	-8.07	-10.57
NH_33	7	87	19.14	-3.29	0.43	-9.14	-3.14	-8.00	-3.57	-8.57	-3.36	-5.00
NH_29	7	89	18.29	-1.57	-0.71	-7.86	-4.57	-8.43	-7.14	-8.14	-5.86	-6.57
NH_26	7	90	15.71	-2.86	-0.57	-8.71	-5.00	-5.86	-4.14	-7.29	-4.57	-2.86
NH_24	7	93	15.14	-6.14	-2.29	-7.43	-3.00	-10.86	-6.71	-9.14	-4.86	-8.00
NH_20	8	98	13.14	-3.29	-0.57	-6.43	-4.57	-8.86	-5.14	-7.64	-4.86	-4.57
NH_32	8	98	19.14	-3.86	-0.29	-4.43	-3.57	-6.71	-6.00	-5.57	-4.79	-5.86
NH_22	8	101	18.29	-5.71	-3.43	-10.43	-4.86	-10.57	-6.57	-10.50	-5.71	-7.86
NH_14	8	103	11.43	-1.57	-0.57	-9.14	-4.14	-9.43	-6.43	-9.29	-5.29	-6.86
NH_27	9	109	17.71	-5.00	-1.29	-13.29	-6.71	-8.14	-6.29	-10.71	-6.50	-9.43
NH_36	9	111	12.86	-5.00	-0.29	-10.29	-8.00	-10.00	-7.00	-10.14	-7.50	-9.71
NH_10	9	112	15.14	-3.00	-2.43	-5.43	-3.43	-7.29	-7.71	-6.36	-5.57	-4.14
NH_17	9	116	12.29	-3.14	-0.29	-8.71	-4.71	-9.71	-7.43	-9.21	-6.07	-4.14
NH_18	9	116	10.29	-6.00	0.43	-6.71	-4.71	-12.71	-6.43	-9.71	-5.57	-8.29
NH_07	10	120	26.00	-5.29	-0.57	-10.00	-4.14	-8.14	-2.00	-9.07	-3.07	-5.71
NH_12	10	120	9.43	-7.86	-2.00	-11.86	-5.43	-12.14	-9.29	-12.00	-7.36	-8.57
NH_25	10	121	10.00	-7.86	-0.71	-15.57	-5.86	-13.29	-7.86	-14.43	-6.86	-10.29
NH_34	10	124	15.71	-6.43	-3.00	-11.43	-6.57	-10.00	-5.86	-10.71	-6.21	-6.14
NH_13	10	125	10.57	-4.14	-4.57	-10.43	-8.00	-13.43	-8.00	-11.93	-8.00	-7.71
NH_28	10	126	16.86	-5.14	-3.29	-10.57	-6.71	-12.14	-7.43	-11.36	-7.07	-7.57
NH_15	11	132	12.00	-6.57	-1.29	-10.57	-7.71	-9.29	-7.29	-9.93	-7.50	-6.43
NH_30	11	135	12.29	-5.86	-1.00	-8.71	-7.86	-12.57	-8.71	-10.64	-8.29	-8.00
NH_42	11	141	7.43	-8.29	-4.43	-14.29	-9.57	-13.14	-8.00	-13.71	-8.79	-13.00
NH_40	11	143	15.71	-7.29	-3.86	-11.43	-10.14	-11.14	-9.71	-11.29	-9.93	-10.71
NH_35	12	145	10.29	-6.14	-3.00	-9.29	-6.71	-12.43	-10.14	-10.86	-8.43	-9.86
NH_08	12	147	11.71	-5.43	0.14	-8.00	-6.43	-13.71	-8.71	-10.86	-7.57	-7.86
NH_16	12	151	9.14	-7.57	-3.14	-14.71	-6.00	-11.86	-10.00	-13.29	-8.00	-7.00
NH_23	12	153	8.00	-8.43	-3.14	-12.71	-7.71	-15.14	-8.29	-13.93	-8.00	-11.43
NH_37	12	154	10.86	-7.14	-2.00	-13.71	-7.57	-13.29	-8.14	-13.50	-7.86	-5.14
NH_38	12	154	15.14	-6.86	-4.14	-14.00	-7.43	-11.57	-7.00	-12.79	-7.21	-4.14

APPENDIX R

MEAN RTS DATA FOR NH PEDIATRIC SUBJECTS

		Front/ Front		Front/ Impaired (Right)		Front/ Normal (Left)		Front/ Side		Front/ Impaired & Normal
Age (years)	**Quiet**	**TTB**	**SSN**	**TTB**	**SSN**	**TTB**	**SSN**	**TTB**	**SSN**	**TTB**
6	19.66	-1.89	-0.74	-6.34	-4.00	-7.43	-4.83	-6.89	-4.41	-5.43
7	15.89	-4.17	-0.97	-10.09	-4.46	-9.11	-6.23	-9.60	-5.34	-6.60
8	15.50	-3.61	-1.21	-7.61	-4.29	-8.89	-6.04	-8.25	-5.16	-6.29
9	13.66	-4.43	-0.77	-8.89	-5.51	-9.57	-6.97	-9.23	-6.24	-7.14
10	14.76	-6.12	-2.36	-11.64	-6.12	-11.52	-6.74	-11.58	-6.43	-7.67
11	11.86	-7.00	-2.64	-11.25	-8.82	-11.54	-8.43	-11.39	-8.63	-9.54
12	10.86	-6.93	-2.55	-12.07	-6.98	-13.00	-8.71	-12.54	-7.85	-7.57

APPENDIX S

INDIVIDUAL SRM DATA FOR NH PEDIATRIC SUBJECTS

			Front/ Impaired (Right)		Front/ Normal (Left)		Front/ Side		Front/ Impaired & Normal
Subject Code	Age (years)	Age (months)	TTB	SSN	TTB	SSN	TTB	SSN	TTB
NH_31	6	72	2.57	2.57	6.71	4.86	4.64	3.71	-0.43
NH_39	6	72	0.86	3.57	4.43	0.57	3.00	2.07	3.00
NH_06	6	74	5.86	3.29	7.14	5.86	6.50	4.57	5.71
NH_09	6	80	4.71	2.29	4.14	3.86	4.43	3.07	3.71
NH_21	6	80	8.29	4.57	5.29	5.29	6.79	4.93	5.71
NH_05	7	84	10.29	4.86	5.43	7.86	7.86	6.36	3.57
NH_33	7	87	5.86	3.57	4.71	4.00	5.29	3.79	1.71
NH_29	7	89	6.29	3.86	6.86	6.43	6.57	5.14	5.00
NH_26	7	90	5.86	4.43	3.00	3.57	0.00	4.00	0.00
NH_24	7	93	1.29	0.71	4.71	4.43	3.00	2.57	1.86
NH_20	8	98	3.14	4.00	5.57	4.57	4.36	4.29	1.29
NH_32	8	98	0.57	3.29	2.86	5.71	1.71	4.50	2.00
NH_22	8	101	4.71	1.43	4.86	3.14	4.79	2.29	2.14
NH_14	8	103	7.57	3.57	7.86	5.86	7.71	4.71	5.29
NH_27	9	109	8.29	5.43	3.14	5.00	4.43	5.21	4.43
NH_36	9	111	5.29	7.71	5.00	6.71	5.14	7.21	4.71
NH_10	9	112	2.43	1.00	4.29	5.29	3.36	3.14	1.14
NH_17	9	116	5.57	4.43	6.57	7.14	6.07	5.79	1.00
NH_18	9	116	0.71	5.14	6.71	6.86	3.71	6.00	2.29
NH_07	10	120	4.71	3.57	2.86	1.43	3.79	2.50	0.43
NH_12	10	120	4.00	3.43	4.29	7.29	4.14	5.36	0.71
NH_25	10	121	7.71	5.14	5.43	7.14	6.57	6.14	2.43
NH_34	10	124	5.00	3.57	3.57	2.86	4.29	3.21	-0.29
NH_13	10	125	6.29	3.43	9.29	3.43	7.79	3.43	3.57
NH_28	10	126	5.43	3.43	7.00	4.14	2.43	3.79	2.43
NH_15	11	132	4.00	6.43	2.71	6.00	3.36	6.21	-0.14
NH_30	11	135	2.86	6.86	6.71	7.71	4.79	7.29	2.14
NH_42	11	141	6.00	5.14	4.86	3.57	4.71	4.36	4.71
NH_40	11	143	4.14	6.29	3.86	5.86	3.43	6.07	3.43
NH_35	12	145	3.14	3.71	6.29	7.14	4.71	5.43	3.71
NH_08	12	147	2.57	6.57	8.29	8.86	5.43	7.71	2.43
NH_16	12	151	7.14	2.86	4.29	6.86	5.71	4.86	-0.57
NH_23	12	153	4.29	4.57	6.71	5.14	5.50	4.86	3.00
NH_37	12	154	6.57	5.57	6.14	6.14	6.36	5.86	-2.00
NH_38	12	154	7.14	3.29	4.71	2.86	5.93	3.07	-2.71

APPENDIX T

MEAN SRM DATA FOR NH PEDIATRIC SUBJECTS

	Front/ Impaired (Right)		Front/ Normal (Left)		Front/ Side		Front/ Impaired & Normal
Age (years)	TTB	SSN	TTB	SSN	TTB	SSN	TTB
6	4.46	3.26	5.54	4.09	5.07	3.67	3.54
7	5.91	3.49	4.94	5.26	4.54	4.37	2.43
8	4.00	3.07	5.29	4.82	4.64	3.95	2.68
9	4.46	4.74	5.14	6.20	4.54	5.47	2.71
10	5.52	3.76	5.40	4.38	4.83	4.07	1.55
11	4.25	6.18	4.54	5.79	4.07	5.98	2.54
12	5.14	4.43	6.07	6.17	5.61	5.30	0.64

APPENDIX U

INDIVIDUAL RTS DATA FOR UHL SUBJECTS

				Front/ Front		Front/ Impaired		Front/ Normal		Front/ Impaired & Normal
Subject Code	Age (years)	Age (months)	Quiet	TTB	SSN	TTB	SSN	TTB	SSN	TTB
6_U	6	82	24.29	1.00	0.14	-4.86	-3.00	0.86	3.29	0.29
8_U	8	105	21.71	-1.43	0.29	-5.43	-6.43	-1.57	-3.43	-1.29
9_U	9	113	25.14	-4.86	0.00	-6.71	-7.43	-7.71	-3.43	-4.00
10_U	10	130	26.00	-3.00	-2.57	-9.29	-4.00	-9.00	-5.14	-5.71
9_HA1	9	110	16.86	-3.14	-2.14	-10.43	-7.00	-4.71	-3.57	-4.86
9_HA2	9	112	14.29	-4.00	-1.71	-8.43	-5.43	-3.57	-0.29	-6.57
11_CROS	11	142	21.71	-2.43	-0.86	-4.00	-0.29	-7.29	-2.86	-2.71

APPENDIX V

INDIVIDUAL SRM DATA FOR UHL SUBJECTS

			Front/ Impaired		Front/ Normal		Front/ Impaired & Normal
Subject Code	Age (years)	Age (months)	TTB	SSN	TTB	SSN	TTB
6_U	6	82	5.86	3.14	0.14	-3.14	0.71
8_U	8	105	4.00	6.71	0.14	3.71	-0.14
9_U	9	113	1.86	7.43	2.86	3.43	-0.86
10_U	10	130	6.29	1.43	6.00	2.57	2.71
9_HA1	9	110	7.29	4.86	1.57	1.43	1.71
9_HA2	9	112	4.43	3.71	-0.43	-1.43	2.57
11_CROS	11	142	1.57	-0.57	4.86	2.00	0.29

APPENDIX W

NORMAL HEARING SUBJECTS' PURE-TONE AVERAGE

	NH Pediatric Subject's Age	Right Ear Pure Tone Average	Left Ear Pure Tone Average
1	6	2	0
2	6	7	7
3	6	7	3
4	6	12	10
5	6	7	8
6	7	10	8
7	7	8	3
8	7	5	2
9	7	5	0
10	7	7	3
11	8	-3	-3
12	8	3	2
13	8	3	3
14	8	2	5
15	9	3	-2
16	9	2	2
17	9	2	-2
18	9	7	7
19	9	2	-3
20	10	-2	-2
21	10	3	0
22	10	0	0
23	10	0	0
24	10	10	7
25	10	2	7
26	11	3	0
27	11	2	-2
28	11	5	5
29	11	0	-2
30	12	3	7
31	12	2	2
32	12	2	-3
33	12	0	0
34	12	2	3
35	12	-2	-2

	NH Adult Subject's Age	Right Ear Pure Tone Average	Left Ear Pure Tone Average
1	21	0	-2
2	19	2	0
3	20	5	2
4	20	5	5
5	20	-2	-3
6	20	10	10
7	19	0	3
8	21	2	2
9	19	2	2
10	20	3	0
11	20	13	10
12	19	0	0
13	20	3	3
14	20	5	2
15	23	3	2
16	28	-2	3
17	20	3	2
18	23	5	5

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