SPATIAL HEARING AND FUNCTIONAL AUDITORY SKILLS OF CHILDREN WHO HAVE UNILATERAL HEARING LOSS

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ABSTRACT

Nicole Elizabeth Corbin: Spatial Hearing and Functional Auditory Skills in Children who have Unilateral Hearing Loss
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Children with unilateral hearing loss (UHL) are at increased risk for a range of developmental difficulties and delays, but there is substantial variability in developmental outcomes among this population. One explanation for the deficits observed among this population is that children with UHL have a reduced ability to compare sounds arriving at the two ears, which is critical for spatial hearing. Few studies have investigated the specific nature of the spatial hearing deficits that children with UHL experience. Defining this population's spatial hearing deficits is critical for understanding and remediating the factors that contribute to the marked differences in developmental outcomes observed among children with UHL.

The goal of this dissertation was to clarify the spatial hearing deficits experienced by children with UHL in natural listening environments. This goal was accomplished in two experiments under the following specific aims: (1) evaluate the effect of UHL on children's ability to benefit from spatial separation of target and masker stimuli (spatial release from masking, SRM) for speech recognition in two-talker speech and speech-shaped noise, (2) assess localization on the azimuthal plane, and (3) determine the association between SRM and functional listening abilities as assessed by parent report for children with UHL. The first experiment addressed Aim 1 in a group of school-age children and adults with normal hearing who completed the experiment both with and without an acute simulated conductive UHL. The second experiment addressed Aims 1 through 3 in a group of children with longstanding sensorineural or mixed UHL, age-matched peers with normal hearing, and adults with normal hearing. Results from Aim 1 suggest that the real-world spatial hearing deficits resulting from UHL depend on the UHL type, degree, and/or duration, as well as characteristics of the listening environment. Findings from Aim 2 provide new insight into the spatial hearing cues used by children with UHL to localize sounds. Under Aim 3, results suggest that parent report of children’s functional hearing is associated with SRM for children with UHL. The findings from this dissertation provide a basis for our understanding of the deficits and individual differences observed in children with UHL.

To my best friend and biggest cheerleader, you told me in our final weeks together that I am so much of you and more. The veracity of that statement is the reason this was possible. Your light shines brighter through me every day that passes; I am honored. Thank you for showing me the way. I love you forever.

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LIST OF ABBREVIATIONS AND SYMBOLS

α	alpha level
A	acquired
ABR	auditory brainstem response
ANOVA	analysis of variance
ANSI	American National Standards Institute
AP	all-pass
APHAP	Parent’s Version of the Abbreviated Profile of Hearing Aid Performance
BKB	Bamford-Kowal-Bench
BN	Background Noise
C	congenital
Co-loc	co-located target and masker stimuli
Contra-UHL	masker presented on the side contralateral to the unilateral hearing loss
CRM	Coordinate Response Measure
CROS	Contralateral Routing of Signal
dB	decibel
df	degrees of freedom
EC	Ease of Communication
EVA	Enlarged Vestibular Aqueduct Syndrome
F	F-statistic
F	female
FM	frequency modulation
ft	feet
HINT-C	Hearing In Noise Test-Children

HL	hearing level
HP	high-pass
hr	hour
Hz	Hertz
ILD	interaural level difference
Ipsi-UHL	masker presented on the side ipsilateral to the unilateral hearing loss
ITD	interaural time difference
JCIH	Joint Committee on Infant Hearing
kHz	kilohertz
L	left
LP	low-pass
M	mean
m	meter
M	male
MAPPID-N	Mandarin Pediatric Lexical Tone and Disyllabic Word Picture Identification Task in Noise
MATLAB	matrix laboratory; a computing environment and programming language
min	minute
MLD	masking level difference
ms	millisecond
n	sample size; number of participants
NH	normal hearing
NRR	noise reduction rating
p	p-value; level of significance

η^2	eta squared; effect size
Ph.D.	Doctor of Philosophy
PPVT	Peabody Picture Vocabulary Test
PTA	pure-tone average
R	right
rmANOVA	repeated-measures analysis of variance
RMS	root-mean-square
s	second
SD	standard deviation
SII	Speech Intelligibility Index
simUHL	simulated unilateral hearing loss
SNR	signal-to-noise ratio
SPL	sound pressure level
SPSS	statistical package for the social sciences
SRM	spatial release from masking
$\mathrm{SRM}_{\mathrm{Contra\text{-}UHL}}$	spatial release from masking when the masker is presented on the side contralateral to the unilateral hearing loss
$\mathrm{SRM}_{\mathrm{Ipsi\text{-}UHL}}$	spatial release from masking when the masker is presented on the side ipsilateral to the unilateral hearing loss
SRT	speech recognition threshold
SRT[no-plug/co-loc]	speech recognition threshold obtained without an earplug or earmuff when the masker is presented co-located with the target
SRT[no-plug/msk-side]	speech recognition threshold obtained without an earplug or earmuff when the masker is presented to either side
SRT[simUHL/co-loc]	speech recognition threshold obtained in the presence of a simulated unilateral hearing loss when the masker is co-located with the target

SRT[simUHL/msk-contra]	speech recognition threshold obtained in the presence of a simulated unilateral hearing loss when the masker is presented on the side contralateral to the simulated unilateral hearing loss
SRT[simUHL/msk-ipsi]	speech recognition threshold obtained in the presence of a simulated unilateral hearing loss when the masker is presented on the side ipsilateral to the simulated unilateral hearing loss
$\text{SRT}_{\text{Co-loc}}$	speech recognition threshold obtained when the target and masker are co-located
$\text{SRT}_{\text{Contra-UHL}}$	speech recognition threshold obtained when the masker is presented on the side contralateral to the unilateral hearing loss
$\text{SRT}_{\text{Ipsi-UHL}}$	speech recognition threshold obtained when the masker is presented on the side ipsilateral to the unilateral hearing loss
SSN	speech-shaped noise
SSQP	Speech, Spatial, Qualities Scale for Parents of children with hearing loss
TTB	two-talker child babble
TTS	two-talker speech
UHL	unilateral hearing loss
UNC	The University of North Carolina at Chapel Hill
UNHS	Universal Newborn Hearing Screening
^{o}	degrees

CHAPTER 1: INTRODUCTION

Children with unilateral hearing loss (UHL) are at an increased risk for academic, cognitive, intellectual, social-emotional, speech, and language problems relative to their peers with normal hearing (Bess & Tharpe, 1986; Bovo et al., 1988; Culbertson & Gilbert, 1986; Ead, Hale, DeAlwis, & Lieu, 2013; Jensen, Johansen, & Børre, 1989; Lieu, 2004; Lieu, Karzon, Ead, & Tye-Murray, 2013; Lieu, Tye-Murray, & Fu, 2012; McKay, Gravel, & Tharpe, 2008; McKay et al., 2008; Oyler, Oyler, & Matkin, 1988; Porter, Sladen, Ampah, Rothpletz, & Bess, 2013). However, there are substantial individual differences in these developmental outcomes among children with UHL, and the factors responsible for these differences remain unknown. The field of audiology currently lacks assessment tools to predict which children with UHL are most at risk for functional communication and other developmental deficits. This leads to a costly, failure-based model of audiological management for this population (Fitzpatrick, Whittingham, & Durieux-Smith, 2014; Knightly, McKay, Marsh, & Gravel, 2007).

A potential explanation for the current void regarding audiologic assessments is that children with UHL often have poor spatial hearing abilities (e.g., Bess, Tharpe, & Gibler, 1986; Bovo et al., 1988; Jensen et al., 1989; Ruscetta, Arjmand, & Pratt, 2005). This deficit has important real-world consequences but is rarely assessed clinically. As a first step towards improving the audiologic assessment and management of children with UHL, it is important to clarify the conditions under which UHL limits the functional auditory performance of school-age children in complex, multi-source environments. We must understand the challenges faced by individual children with UHL in real-world environments so that we can predict which children with UHL are at higher risk for functional delays. This knowledge will allow us to advance individualized intervention for those children. One premise of the work described here is that spatial hearing abilities mediate real-world outcomes for children with UHL; this is tested directly in Chapter 3.

Importance of Spatial Hearing

Spatial hearing refers to the ability to use the distinct paths by which sounds travel to the two ears in order to make sense of the environment (Blauert, 1997). Binaural difference cues, or differences in the timing and intensity of sounds arriving at the two ears, underlie spatial hearing on the horizontal plane (Blauert, 1982, 1997; Brungart & Rabinowitz, 1999; Shaw, 1974; Zurek, 1993). Access to typical binaural difference cues through normal bilateral hearing facilitates accurate sound source localization and speech recognition in noise (Blauert, 1982; Blauert, 1997; Hartmann, 1983; Levitt & Rabiner, 1967a, 1967b; Rakerd & Hartmann, 2010; Shaw, 1974; Zurek, 1993). Additionally, binaural difference cues support spatial release from masking (SRM), which in this context refers to the improvement in speech recognition observed when a masker source is moved from the target location to a different location (Bronkhorst & Plomp, 1992). Children with UHL are at a disadvantage when localizing sounds and understanding speech in complex multi-source environments due to absent or impoverished binaural difference cues.

There is growing recognition that spatial hearing is critical for the developing child. Children spend the majority of their days learning in environments that are replete with multiple sources of sound that originate from different locations in space. In such environments, performance often hinges on the ability to locate and perceptually segregate target speech while discounting competing sounds that interfere with the peripheral encoding of the target speech, the central processing of the target speech, or both. The masked speech recognition abilities of children with UHL have been assessed in the laboratory and clinic using competing sounds such as cafeteria noise or multi-talker babble (Bess et al., 1986; Jensen et al., 1989; Kenworthy, Klee, & Tharpe, 1990; Ruscetta et al., 2005). These maskers are associated with primarily energetic masking. Energetic masking refers to reduction in performance that results from overlapping excitation patterns of target speech and masker stimuli at the level of the auditory periphery (Fletcher, 1940). However, evidence suggests that speech recognition in the presence of competing speech involves both energetic and informational masking (Brungart, 2001; Brungart, Chang, Simpson, & Wang, 2006; Brungart, Simpson, Ericson, & Scott, 2001; Carhart, Tillman, & Greetis, 1969; Freyman, Balakrishnan, & Helfer, 2001, 2004; Freyman, Helfer, McCall, & Clifton, 1999). Informational masking refers to masking that cannot be attributed to overlapping excitation patterns of target speech and masker stimuli on the basilar membrane. Rather, informational masking is thought to reflect central auditory processes involved in segregating and selectively attending to target as opposed to masker stimuli—processes that may be critical for learning in the classroom. When the task is speech recognition, informational masking is commonly associated with maskers composed of speech produced by a small number of talkers (Freyman et al., 2004).

There are few data pertinent to the masked speech recognition abilities of children with UHL under conditions associated with informational masking. There are even fewer data relevant to SRM in children with UHL under conditions associated with informational masking. This lack of data represents a critical gap in the literature in light of evidence suggesting that binaural difference cues are particularly beneficial for speech recognition in the presence of multiple, spatially separate sounds that produce informational masking (Bronkhorst & Plomp, 1988; Culling, Hawley, & Litovsky, 2004; Glyde et al., 2013; Hawley, Litovsky, & Culling, 2004; Rothpletz, Wightman, & Kistler, 2012). Assessing performance under such conditions has the potential to capture individual differences in audiologic outcomes and provide information regarding functional communication abilities. Furthermore, it is possible that susceptibility to informational masking could provide insight into factors contributing to the academic, cognitive, intellectual, social-emotional, speech, and language deficits observed among children with UHL. Support for this notion comes from data on children with bilateral sensorineural hearing loss. These data indicate that speech recognition in competing speech from two talkers, but not speech-shaped noise, is associated with parent's reports of their children's everyday communication challenges (Hillock-Dunn, Taylor, Buss, & Leibold, 2015). For those children, speech-on-speech recognition was not associated with clinical measures of better-ear pure-tone average or word recognition in quiet (Hillock-Dunn et al., 2015; Leibold, Hillock-Dunn, Duncan, Roush, & Buss, 2013). Additionally, individual differences among adults with normal hearing for SRM in competing speech are thought to be related to selective listening abilities (Swaminathan et al., 2015), which are essential to optimal outcomes in the areas of development noted above.

The ability to localize sound sources is critical for safety and environmental awareness. Sound source localization is also beneficial for communication in multi-source environments. Previous studies indicate that children with UHL have difficulty localizing sound sources on the azimuthal plane (Bess et al., 1986; Bovo et al., 1988; Humes, Allen, & Bess, 1980; Newton, 1983; Reeder, Cadieux, & Firszt, 2015). However, some children with UHL localize better than expected based on the availability of binaural difference cues (Newton, 1983). While it is generally accepted that listeners with normal hearing primarily use binaural difference cues for sound source localization on the azimuthal plane (Blauert, 1982; Kistler & Wightman, 1992;

Macpherson & Middlebrooks, 2002), it is possible that some children with UHL learn to use monaural cues to localize sounds on the azimuthal plane (Slattery & Middlebrooks, 1994). Knowing the extent to which a child relies on monaural cues for sound source localization is important for audiologic management, particularly since the provision of a behind-the-ear or implantable assistive device may disrupt such cues. The majority of previous studies investigating the sound source localization abilities in children with UHL have utilized 500 Hz and 3000 Hz pure tones (Bess et al., 1986; Bovo et al., 1988; Humes et al., 1980; Newton, 1983); these stimuli provide limited insight regarding how children with UHL localize complex sounds. Moreover, the use of pure tones to examine the localization abilities of children with UHL precludes an assessment of the extent to which this population may use monaural spectral cues to localize more common natural sounds on the azimuthal plane.

The paucity of systematic investigations into the factors responsible for the observed spatial hearing deficits experienced by children with UHL limits the audiologic assessment and management of pediatric UHL. Few studies have explored this population's speech recognition abilities under conditions associated with informational masking and spatial separation of target and masker stimuli. Additionally, minimal data exist regarding this population's weighting of binaural and monaural cues to source location on the azimuthal plane. These represent critical gaps in the literature considering that (1) susceptibility to informational masking is correlated with the real-world communication abilities of children with bilateral sensorineural hearing loss (Hillock-Dunn et al., 2015), (2) SRM in the presence of informational masking has been argued to provide insight into factors that contribute to individual differences in masked speech recognition for adults (Blauert, 1982; Macpherson & Middlebrooks, 2002; Wightman & Kistler, 1992), and (3) the ability to localize sound sources is critical for children, who spend a large proportion of their time in multi-source environments. The experiments reported in this dissertation addressed these critical gaps through the following specific aims:

(1) Evaluate the effect of UHL on children’s SRM in two-talker speech and speech-shaped noise.

(2) Assess localization on the azimuthal plane in children with permanent sensorineural or mixed UHL.

(3) Determine the association between SRM (Aim 1) and functional listening abilities as assessed by parent report of children with permanent UHL.

Experimental results relevant to these aims are described in Chapters 2 and 3. Chapter 2 describes an experiment where moderate conductive UHL was simulated in school-age children and adults with normal bilateral hearing. Effects on SRM were evaluated. Chapter 3 describes an experiment with a separate cohort of participants that included children who had permanent sensorineural or mixed UHL, age-matched peers with NH, and adults with NH. The effect of permanent UHL was evaluated for localization and SRM. Parents of children with UHL completed questionnaires evaluating their children’s listening challenges hearing in noise, and correlational analyses were conducted to examine the relationship between children’s SRM and their questionnaire scores. Consistent methods for evaluating SRM were used in Chapters 2 and 3, allowing a comparison between the effects UHL with respect to duration of hearing loss (acute versus longstanding), type of hearing loss (conductive versus sensorineural or mixed), and degree of hearing loss (moderate versus profound). The final chapter summarizes the findings from Chapters 2 and 3, and proposes future directions for this area of research.

CHAPTER 2: SPATIAL RELEASE FROM MASKING IN CHILDREN: EFFECTS OF SIMULATED UNILATERAL HEARING LOSS[1]

Introduction

Pediatric permanent unilateral hearing loss (UHL) represents a growing concern in the audiology community. This concern is due to the wide variability in developmental outcomes observed among children with permanent UHL and the lack of consensus regarding the audiologic management for this population. Children with permanent UHL often experience developmental difficulties, even in cases of mild UHL. This could be due, in part to reduced access to binaural cues, which are important for speech perception in complex listening environments (Bess et al., 1986; Brookhouser, Worthington, & Kelly, 1991; Lieu et al., 2013, 2012; Lieu, Tye-Murray, Karzon, & Piccirillo, 2010; Quigley & Thomure, 1969). Specifically, binaural cues facilitate spatial release from masking (SRM) when a target talker (e.g., the teacher) is spatially separated from background talkers (e.g., classmates). For adults with normal hearing, SRM is more pronounced when the masker is acoustically and perceptually complex (e.g., 1 or 2 competing talkers) relative to when the masker is noise or babble composed of many talkers (Arbogast, Mason, & Kidd, 2002; Freyman et al., 2001). Adults with permanent or simulated UHL achieve significantly less SRM than their counterparts with normal bilateral hearing, and this deficit is exacerbated in the presence of relatively complex maskers (e.g., two-talker speech [TTS]; Marrone, Mason, & Kidd, 2008; Rothpletz et al., 2012). While previous

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studies demonstrate that children with permanent UHL experience degraded speech understanding in relatively steady maskers (Bess et al., 1986; Lieu et al., 2013; Ruscetta et al., 2005), their ability to achieve SRM in the presence of complex maskers has not been systematically investigated. This is a critical gap in the literature considering recent evidence that the real-world performance of children with permanent bilateral hearing loss is better predicted by speech recognition in a two-talker than a steady noise masker (Hillock-Dunn et al., 2015). The purpose of this study was twofold: 1) to determine the effect of an acute simulated UHL on SRM in TTS and speech-shaped noise (SSN) for children, and 2) to develop a procedure to be used in future studies that will assess SRM in children who have permanent UHL.

Population-based prevalence estimates of permanent UHL among children ages 6 to 19 years range from 3% to 6%, depending on how UHL is defined (Ross, Visser, Holstrum, Qin, & Kenneson, 2010). Conventional wisdom has been that, with one normal-hearing ear, children with UHL will acquire speech and language normally and achieve age-appropriate developmental milestones. It is now recognized that children with UHL are at an increased risk for academic, cognitive, social-emotional, speech, and language problems relative to their peers with normal hearing in both ears (Bess & Tharpe, 1986; Borg et al., 2002; Ead et al., 2013; Lieu et al., 2010). For instance, an estimated 36% to 54% of school-age children with UHL require educational assistance and/or receive speech-language therapy, and at least one-third of them experience behavioral problems in the classroom (Bess & Tharpe, 1986; Dancer, Burl, & Waters, 1995; Lieu et al., 2012; Oyler et al., 1988; Sedey, Carpenter, & Stredler-Brown, 2002). However, there are considerable individual differences in developmental outcomes among children with UHL. Despite increased early identification, variability in outcomes contributes to the lack of consensus regarding audiologic management for this population and results in a costly, failure-based model of intervention (Fitzpatrick et al., 2014; Knightly et al., 2007; Porter & Bess, 2011). The field of audiology currently lacks assessment tools that predict which children with UHL are most at risk for functional communication deficits. A potential explanation for this void is that the majority of conventional clinical tools fail to capture the difficulties faced by children with UHL in the complex listening conditions they encounter in their everyday lives.

One of the reasons children with UHL often experience poorer outcomes than their peers with normal bilateral hearing is their lack of access to binaural cues. Head shadow effect, binaural squelch, and binaural summation are the three binaural effects traditionally associated with the benefit of listening with two ears relative to one in multi-source environments (Bronkhorst & Plomp, 1988). In natural listening environments, listeners often turn to face a target of interest, such that it originates from 0° azimuth in listener-centric coordinates. Under these conditions, the target stimulus reaching the two ears is functionally identical. In contrast, when a masker is spatially separated from the target in azimuth, it will arrive at the listener's ears at different times and with different intensities. Listeners are able to use these interaural time differences (predominantly below 1500 Hz) and interaural intensity differences (predominantly above 1500 Hz) to their advantage. The signal-to-noise ratio (SNR) will be better at the ear furthest from the masker source due to the high-frequency acoustic shadow the head casts over that ear. By virtue of this head shadow effect, the listener has the opportunity to attend to the ear with the better SNR to improve speech recognition performance by 3 to 8 dB (Bronkhorst & Plomp, 1988). Listeners also use information from the ear with the less favorable SNR. Access to interaural time differences associated with the target and masker stimuli at the two ears improves listeners' performance by 3 to 7 dB; this effect is known as binaural squelch (Bronkhorst & Plomp, 1988; Hawley et al., 2004; Levitt & Rabiner, 1967a, 1967b). Even when the target and masker both originate from the front of a listener and there are no interaural time or level differences, listeners benefit from having access to two neural representations of the target and masker stimuli. This binaural cue is known as binaural summation, and it typically improves speech recognition performance in noise by 1 to 3 dB (Bronkhorst & Plomp, 1988; Davis, Haggard, & Bell, 1990; Gallun, Mason, & Kidd, 2005).

The binaural benefit associated with spatially separating the target and masker on the azimuth is referred to as SRM. Under complex listening conditions, this improvement is thought to rely largely on auditory stream segregation, in which interaural difference cues are used to perceptually differentiate the target and masker streams (Bregman, 1990; Bronkhorst & Plomp, 1988; Freyman et al., 1999; Licklider, 1948; Zurek, 1993). SRM is often expressed as the difference in speech recognition performance between a condition in which target and masker stimuli are co-located in the front of the listener and a condition in which the target and masker stimuli are perceived to originate from different locations on the azimuthal plane. By assessing SRM, we can estimate the extent to which a listener uses binaural cues for hearing in complex listening environments.

In adults, SRM increases as target-masker similarity or stimulus uncertainty increases, presumably due to the increasing role of informational masking when the target and masker are co-located (Arbogast et al., 2002; Brungart, 2001; Culling et al., 2004; Durlach et al., 2003; Freyman et al., 2001; Hawley et al., 2004). Speech recognition in steady maskers such as SSN is traditionally associated with energetic masking (e.g., Fletcher, 1940; also see Stone & Moore, 2014). Energetic masking is the consequence of overlapping excitation patterns on the basilar membrane, reducing the fidelity with which target and masker stimuli are represented in the auditory periphery. Speech recognition in competing speech involves both energetic and informational masking. In contrast to energetic masking, informational masking reflects a reduced ability to segregate and selectively attend to a particular auditory object despite adequate peripheral encoding (Brungart, 2001). For a given angular separation, the SRM observed for informational maskers is typically much larger than observed for energetic maskers. This is thought to reflect the greater segregation challenge in informational maskers. On average, adults with normal hearing bilaterally achieve 6-7 dB SRM in the presence of noise maskers, but around 18 dB SRM in the presence of one or two competing talkers (Arbogast et al., 2002; Bronkhorst, 2000; Carhart et al., 1969; Hawley et al., 2004; Kidd, Mason, Rohtla, & Deliwala, 1998).

Permanent or simulated UHL reduces SRM in adults. Rothpletz et al. (2012) demonstrated that SRM is essentially eliminated for adults with mild to profound permanent UHL for a speech-on-speech recognition task involving target and masker sentences that were digitally processed to substantially reduce energetic masking. SRM is also eliminated for a speech-on-speech recognition task when adults with normal hearing listen with an earplug and earmuff to simulate a mild UHL (average attenuation = 38.1 dB; Marrone et al., 2008). Limited access to the binaural difference cues supporting SRM may not fully explain the deficit associated with UHL in adults, however. When the target and masker are co-located in front of the listener, a condition in which both interaural time and level differences are functionally eliminated, adults with mild to profound UHL perform up to 4.5-dB worse than adults with normal hearing under conditions associated with substantial informational masking (Rothpletz et al., 2012). These results indicate that UHL degrades speech perception for adults in the presence of informational masking, whether or not interaural difference cues are available. Moreover, this decrease in performance for adults with UHL is observed even for mild hearing losses.

Similar to adults, children with normal hearing achieve greater SRM in the presence of informational relative to energetic masking. In general, SRM in young children with normal hearing ranges from 3 to 11 dB, depending on the stimuli and test conditions used (Litovsky, 2005; Lovett, Kitterick, Huang, & Summerfield, 2012). While some studies indicate that SRM continues to develop through childhood for complex maskers, (Yuen & Yuan, 2014), other data indicate that SRM is mature by 3 years of age (Litovsky, 2005). On a four-alternative forced-choice spondee identification task, Johnstone and Litovsky (2006) found that 5- to 7-year-olds achieved significantly greater SRM in the presence of unaltered speech and time-reversed speech (3.4 dB and 6.7 dB, respectively) relative to modulated noise (0.5 dB). The overall finding that children achieved greater SRM for speech-based relative to noise maskers was interpreted as being due to greater informational masking. Although it is unclear why the SRM for time-reversed speech was greater than that observed for unaltered speech, the authors posited that the novelty of the time-reversed speech may have resulted in relatively greater informational masking, and therefore greater SRM.

There are relatively few data pertinent to SRM in school-age children with permanent sensorineural UHL, but available data indicate reduced benefit of target/masker spatial separation and poorer speech recognition overall for children with UHL (e.g., Bess et al., 1986; Bovo et al., 1988; Jensen et al., 1989; Kenworthy et al., 1990; Lieu et al., 2013; Noh & Park, 2012; Reeder et al., 2015; Updike, 1994). For example, Reeder et al. (2015) reported that 7- to 16-year-olds with moderately-severe to profound sensorineural UHL performed worse than age-matched peers with normal hearing on a range of tasks. These tasks included: monosyllabic word recognition in quiet and four-talker babble, sentence recognition in spatially diffuse restaurant noise, and spondee recognition in quiet, single-talker speech, and multi-talker babble presented from 0°, +90°, or -90° azimuth. While the deficits associated with UHL tended to be largest when the target and masker originated from different locations in space, poorer performance relative to children with normal hearing was also observed in quiet and when the masker was co-located with the target. Poorer performance in children with UHL, even in the absence of a binaural difference cue, is consistent with the results of Bess et al. (1986); that study tested 6- to 13-year-olds with either normal hearing or moderate to severe sensorineural UHL and found a detrimental effect of UHL when the target stimulus was presented in quiet to the ear with normal hearing sensitivity. Data from Bess et al. (1986) also support the idea that the ability to benefit from SRM is related to a child's listening challenges in daily life. Specifically, individual children with UHL who benefitted least from the head shadow effect also tended to experience more difficulty in school than those who were better able to use the head shadow effect (Bess et al., 1986). These studies suggest that children with UHL, who have compromised access to binaural cues, experience marked difficulties in complex listening environments characterized by multiple, co-located or spatially separate competing sound sources.

While previous studies of spatial hearing in children demonstrate a detrimental effect of UHL, none of those studies has explicitly considered the effect of informational versus energetic masking. We know that informational masking is associated with an especially pronounced SRM in children with normal hearing (Johnstone & Litovsky, 2006; Misurelli & Litovsky, 2015), and initial data are consistent with the idea that UHL in children is particularly detrimental in speech-based maskers (Reeder et al., 2015). Further motivation for considering children's performance in the presence of informational masking is based on recent data from Hillock-Dunn et al. (2015). That study evaluated masked speech recognition in children with *bilateral* sensorineural hearing loss, with the target and masker both coming from 0° azimuth. Parental reports of their children’s everyday communication difficulties were strongly correlated with speech recognition in the TTS masker, but not the SSN masker. These data suggest that children’s susceptibility to informational masking has the potential to provide valuable new information about the communication abilities of children with hearing loss outside the confines of the audiology booth.

The present study was designed to better understand the effects of UHL in children, particularly with respect to SRM in low and high informational masking contexts. The approach was to examine the effects of an acute conductive UHL, produced with an earplug and earmuff, on SRM in TTS and SSN for children and adults with normal bilateral hearing. While there are important differences between conductive and sensorineural hearing loss (reviewed by Gelfand, 2009), and between acute and permanent hearing loss (e.g., Kumpik, Kacelnik, & King, 2010), the goal was to better understand how children and adults with normal hearing sensitivity use the cues available to them under these conditions. Listeners with normal bilateral hearing completed an open-set sentence recognition task in the presence of SSN or TTS. The target was presented from the front of the listener, and the masker was either co-located with the target or spatially separated to one side. Each listener served as his or her own control by completing the SRM task in the context of normal bilateral hearing (no plug) and a simulated UHL.

There were three main predictions. First, SRM was expected to be larger in TTS than in SSN, as observed previously. Considering that SRM is dependent on the quality of binaural cues, it was predicted that the differential effect of masker might only be observed in the no-plug conditions. Second, the simulated UHL was expected to worsen performance in all listening conditions, but particularly in the spatially separated TTS masker. Third, SRM was expected to be smaller for children than for adults in the two-talker masker. This expectation was based on the observations that (1) development of SRM may extend into childhood for complex maskers (Yuen & Yuan, 2014, but see Litovsky, 2005) and (2) the binaural masking level difference (MLD) becomes adult-like later in development for noise stimuli thought to introduce informational masking (Grose, Hall, & Dev, 1997).

Materials and Methods

Participants

Participants were 12 children (ages 8.7 to 10.9 years) and 11 adults (18.5 to 30.4 years). Criteria for inclusion were: (1) air-conduction hearing thresholds less than or equal to 20 dB HL for octave frequencies from 250 Hz to 8000 Hz, bilaterally (American National Standards Institute [ANSI], 2010); (2) native speaker of American English; and (3) no known history of chronic ear disease. This research was approved by the Institutional Review Board of the University of North Carolina at Chapel Hill.

Stimuli and conditions

Target stimuli were Revised Bamford-Kowal-Bench (BKB) sentences (Bench, Kowal, & Bamford, 1979) spoken by an adult female native speaker of American English. The BKB corpus includes 21 lists of 16 sentences, each with 3-4 keywords, for a total of 50 keywords per list. These stimuli have previously been used in our lab to examine masked speech perception for children as young as 5 years of age (e.g., Hall, Buss, Grose, & Roush, 2012). Recordings were made in a sound-treated room, digitized at a resolution of 32 bits and a sampling rate of 44.1 kHz, and saved to disk as wav files. These files were root-mean-square (RMS) normalized and down sampled to 24.4 kHz before presentation.

Each sentence was recorded a minimum of two times. Three adults with normal hearing listened to the sentence corpus to verify the sound quality of the recordings. The adults included two audiology graduate students and one Ph.D.-level research audiologist, all of whom were native speakers of American English. Sentences were presented diotically at a comfortable loudness level through headphones (Sennheiser; HD25). Listeners were instructed to mark any words or sentences with undesirable sound quality characteristics (e.g., distortion, peak clipping, irregular speaking rate, and excessively rising or falling intonation). Based on this feedback, a subset of sentences was re-recorded and edited. Two of the adults conducted a final listening check of the full sentence corpus.

The masker was either TTS or SSN, and it was presented continuously over the course of a threshold estimation track. Following Calandruccio et al. (2014), the two-talker masker was composed of recordings of two female talkers, each reading different passages from the children's story *Jack and the Beanstalk* (Walker, 1999). The female talkers were recorded separately. Each of the individual masker streams was manually edited to remove silent pauses of 300 ms or greater. The rationale for this editing was to reduce opportunities for dip listening. Each masker stream was RMS-normalized before summing. The result was a 1.4-min masker sample, which ended with both talkers saying a complete word. The SSN masker had the same long-term magnitude spectrum as the TTS masker. At the outset of each trial, masker playback started at the beginning of the associated audio file. Due to the nature of the adaptive tracking procedure, each track ended at different time points in the masker.

A custom MATLAB script was used to control selection and presentation of stimuli. Target and masker stimuli were processed through separate channels of a real-time processor (Tucker Davis Technology; RZ6), amplified (Applied Research Technology; SLA-4), and presented through a pair of loudspeakers (JBL; Professional Control 1). Target sentences were always presented from a loudspeaker in front of the listener (0° azimuth). The masker stimulus was either co-located with the target (0° azimuth) or spatially separated to the right (+90° azimuth) or left (-90° azimuth) of the listener.

Procedure

General procedure. Speech reception thresholds (SRTs) were measured to assess performance on an open-set sentence recognition task. Participants were seated in the center of a 7 x 7 ft, single-walled sound-treated booth, approximately 3 ft from each of two loudspeakers. Experimental stimuli were calibrated with the microphone suspended 2 ft above the chair in which participants were seated, at the level of the center of the loudspeaker cone; this was also the approximate position of participants' ears when seated. Chair height was not adjusted for individual listeners. For conditions in which the target and masker were spatially separated, the loudspeaker associated with the target depended on the desired masker position. By changing the physical orientation of the participant's chair, the participant always directly faced the speaker associated with the target stimulus. The side of the simulated UHL and the order of testing in each listening mode (no plug or simulated UHL) were counterbalanced across participants within each age group[2].

In the simulated-UHL listening condition, participants completed the speech recognition task with each masker (TTS and SSN) at 0° azimuth, +90° azimuth, and -90° azimuth. The SRTs in the three simulated UHL conditions will be referred to as SRT[simUHL/co-loc] (target and masker co-located), SRT[simUHL/msk-ipsi] (masker ipsilateral to the simulated UHL), and SRT[simUHL/msk-contra] (masker contralateral to the simulated UHL); see Figure 1 for

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[2] There is no precedent in the literature to expect a difference between SRTs for a masker at +90°or -90° azimuth in normal-hearing listeners who are listening without simulated hearing loss. However, there are inconsistent findings in the literature regarding UHL laterality on patient outcomes (e.g., speech recognition in noise). In this study, laterality of simulated UHL did not have a statistically significant effect on performance.

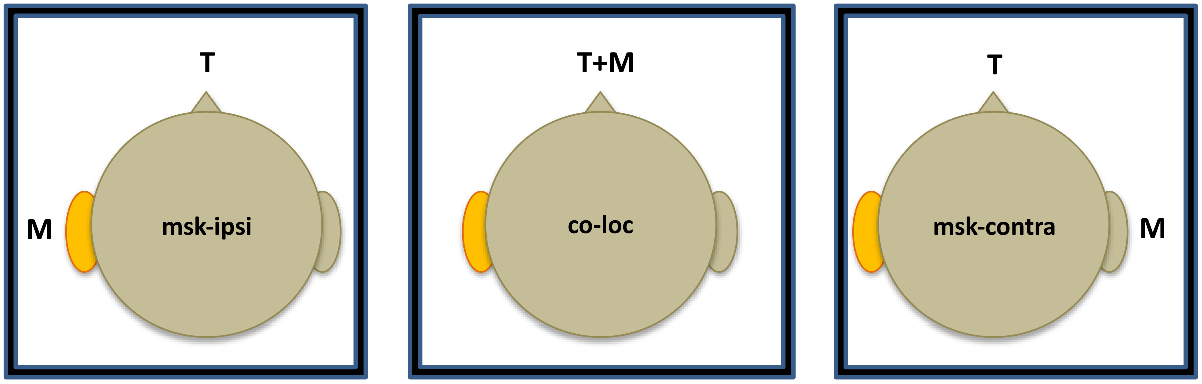
reference. In the presence of a simulated UHL, we expected performance in the spatially separated conditions to be poorer when the masker was contralateral to the simUHL (i.e., on the side of the normal-hearing ear) relative to when it was ipsilateral to the simUHL (i.e., on the side of the ear with simUHL). This prediction was based on the listener’s ability to capitalize on the head-shadow cue in the simUHL/msk-ipsi condition, but not the simUHL/msk-contra condition. In the no-plug listening condition, participants completed the task with the masker at 0° azimuth and +90° azimuth. The SRTs in these two no-plug conditions will be referred to as SRT[no-plug/co-loc] and SRT[no-plug/msk-side], respectively.

Figure 1. Listening conditions

A schematic of the listening conditions tested when the listener has a simulated unilateral hearing loss (simUHL). Orange indicates the ear affected by UHL. From left to right, the first panel illustrates simUHL/msk-ipsi condition, in which the masker is presented ipsilateral to the UHL. The second panel shows the simUHL/co-loc condition, in which the target and masker are co-located in space. The third panel demonstrates the simUHL/msk-contra condition, in which the masker is presented contralateral to the UHL.

T = target stimulus

M = masker stimulus



During testing, participants wore an FM transmitter (Sennheiser; ew 100 G3) with a lapel microphone. The microphone was attached to the participant's shirt, positioned within 6 inches of his/her mouth. The participant's verbal responses were presented to an examiner seated outside the booth via an FM receiver coupled to high-quality headphones (Sennheiser; HD25). This approach optimized the SNR for the observer, who also monitored the participant's face through a window throughout testing.

Participants were informed that they would first hear continuous speech or noise from the front or side loudspeaker, and then a sentence spoken by a female from the front loudspeaker. They were instructed to ignore the continuous background sounds and verbally repeat each sentence produced by the female from the front loudspeaker. Participants were told to make their best guess of the sentence even if they only heard one word because scoring was conducted on a word-by-word basis. The examiner scored each keyword as correct or incorrect. Keywords were only marked "correct" if the entire word was correctly repeated, including pluralization and tense. The maximum response window for each trial was 5 s after the end of the target sentence presentation. If the participant did not respond within this window, the tester marked all keywords as incorrect. Formal feedback was not given; however, encouragement was provided for children through social reinforcement (e.g., smiling and a head nod).

Unilateral hearing loss simulation. Unilateral hearing loss was simulated using a foam earplug [Howard Leight Max Small; Noise Reduction Rating (NRR) 30 dB] and a supra-aural earmuff (Howard Leight Thunder T3; NRR 30 dB), both placed by the examiner. For the UHL simulation, the earplug was deeply inserted into the participant's ear canal, and the supra-aural earmuff was placed over the pinna to optimize attenuation. The supra-aural earmuff was modified to remove the ear cup contralateral to the simulated UHL. The headband of the supra-aural earmuff was adjusted for comfort and to ensure that the contralateral ear was not obstructed. A right unilateral hearing loss was simulated in 6 of 12 children and 6 of 11 adults. The average attenuation provided by the earplug and earmuff combination was measured behaviorally in the sound field at 0° azimuth. Given the amount of testing time required to complete the study, detection thresholds with and without the simulated UHL were only measured for a warble tone at 500 Hz, 1000 Hz, and 2000 Hz. The ear contralateral to the simulated UHL was masked with a 50 dB HL noise band centered on the test frequency, delivered via insert earphone (Etymotic, ER-3A); this insert earphone was not worn during speech recognition testing. Thresholds were assessed with and without the earplug + earmuff combination, and the difference was taken to estimate the amount of attenuation provided by the UHL simulation. This procedure was completed before speech recognition testing for one child and after speech recognition testing for 10 children. Average attenuation values were not obtained for one child due to participant fatigue. Attenuation values were obtained for only two adult participants at the time of the main experiment; additional values were subsequently obtained in seven newly recruited normal-hearing adults (ages 20.1 to 35.1 years). On average, the simulated UHL condition resulted in a moderate flat conductive hearing loss. Additional details appear in the results section.

Threshold estimation. A 1-up, 1-down tracking procedure (Levitt, 1971) was used to estimate speech recognition thresholds corresponding to the average SNR required for 50% correct sentence identification. The overall level of the target plus masker was fixed at 60 dB SPL. This level was chosen based on the range of conversational speech level in noisy environments (Olsen, 1998) and the average attenuation achieved through the UHL simulation. Using a higher overall target plus masker level would have resulted in greater audibility in the simulated UHL condition. Each run was initiated at a SNR of 10 dB. The SNR was increased by increasing the signal level and decreasing the masker level if one or more keywords were missed. The SNR was reduced by decreasing the signal level and increasing the masker level if all keywords were correctly identified. An initial step size of 4 dB was reduced to 2 dB after the first two reversals. Runs were terminated after eight reversals. The SRT was estimated by computing the average SNR at the final six reversals.

The first target sentence presented to a participant was selected randomly from the entire set of BKB sentences. Thereafter, sentences were presented in sequential order, ensuring that no sentences were repeated. Each run required 16-20 sentences. A minimum of two SRTs was estimated for each condition. Data collection in each condition continued until two estimates within 3 dB of each other were obtained. This criterion was typically met with two estimates. Adults required more than two runs at a rate of 15% in SSN and 13% in TTS. Children required more than two runs at a rate of 10% in speech-shaped nose and 12% in TTS. The mean of the two estimates within 3 dB of each other represented the final SRT used for the subsequent analyses. Testing for children required two visits to the laboratory: one to complete the simulated-UHL conditions, and one to complete the no-plug conditions. In the presence of a simulated UHL, total testing time was 1.5 to 2 hrs. It took less than 1 hr to complete testing in the no-plug conditions. Adults completed all testing in 1 visit, typically lasting 2 to 2.5 hrs. All listeners were given breaks throughout testing.

Results were evaluated using repeated-measures analysis of variance (rmANOVA). Subsequent simple main effects testing used Bonferroni adjustment for multiple comparisons. A significance criterion of $\alpha = 0.05$ was adopted. The SRM was quantified as the difference between thresholds obtained when the target and masker were co-located and thresholds obtained when the masker was presented from +90° or -90° from the midline, as follows:

$$\text{SRM}_{\text{No-plug}} = \text{SRT[no-plug/co-loc]} - \text{SRT[no-plug/msk-side]}$$

$$\text{SRM}_{\text{Ipsi-UHL}} = \text{SRT[simUHL/co-loc]} - \text{SRT[simUHL/msk-ipsi]}$$

$$\text{SRM}_{\text{Contra-UHL}} = \text{SRT[simUHL/co-loc]} - \text{SRT[simUHL/msk-contra]}$$

Recall that in the presence of a simulated UHL, we predicted better performance in the simUHL/msk-ipsi relative to simUHL/msk-contra condition due to the listener's ability to capitalize on the head-shadow cue when the masker was on the side of the simulated UHL. Consequently, we expected $\text{SRM}_{\text{Ipsi-UHL}}$ to be greater than $\text{SRM}_{\text{Contra-UHL}}$.

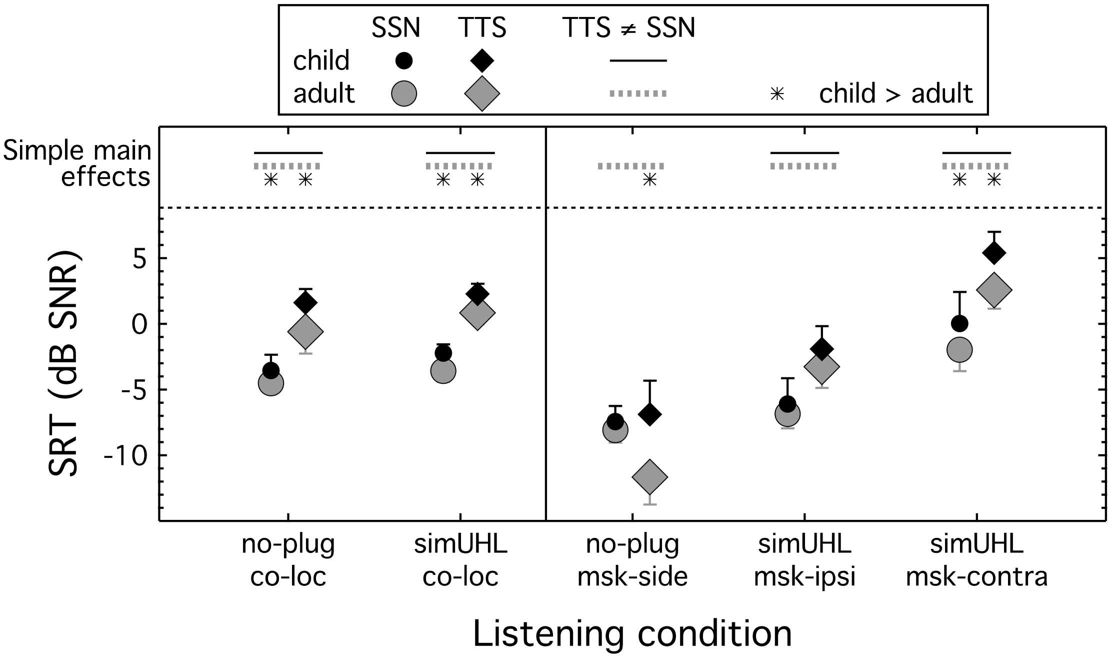
Results

For children, the average amount of attenuation provided by the earplug and earmuff at 500 Hz, 1000 Hz, and 2000 Hz was 44.8 (*SD* = 5.2), 42.3 (*SD* = 6.3), and 39.5 (*SD* = 4.6) dB SPL, respectively. For adults, attenuation at these frequencies was 44.2 (*SD* = 10.4), 47.9 (*SD* = 5.9), and 40.2 (*SD* = 5.1) dB SPL. For both groups, the simulated UHL resulted in a moderate conductive UHL.

Figure 2 shows results of speech recognition testing, with SRTs for children and adults with and without simulated UHL in each target-masker configuration plotted separately. The SRTs obtained in the SSN masker are represented by circles, and those obtained in the TTS masker are represented by diamonds. Shading designates age group, with black symbols representing data for children and gray symbols representing data for adults. Error bars represent one standard deviation. Higher thresholds indicate poorer performance. Stars and lines in the top panel of the figure reflect results of simple main effects testing, described below. Mean SRTs by listener group and condition, as well as the associated standard deviations, are also reported in Table 1.

Figure 2. Group average speech recognition thresholds (SRTs)

Group average SRTs (dB SNR) required to reach 50% correct sentence recognition are shown for children and adults in all listening conditions, indicated on the abscissa. Results in the left panel reflect those obtained in co-located target-masker conditions, while those in the right panel reflect those obtained in spatially separated target-masker conditions. Symbol shape indicates masker condition. Circles indicate SRTs obtained in SSN, while diamonds indicate SRTs obtained in TTS. Symbol shading and size designate age group. Small black symbols represent data for children, and large grey symbols represent data for adults. Error bars represent one standard deviation of the mean. Results of simple main effects testing appear at the top of each panel. Stars indicate significant differences between SRTs of children and adults within a condition. Lines indicate significant effects of masker type within data of either children (solid black lines) or adults (dashed grey lines).



Overall, there was a trend for thresholds to be higher for children than adults, higher in TTS than in SSN, and higher for the simulated-UHL than the no-plug listening conditions. However, the magnitude of these trends differed in detail across listening conditions, maskers, and age groups. For example, the mean child/adult difference in the no-plug/msk-side condition was 4.8 dB in TTS, but only 0.6 dB in SSN. Average SRTs were more than 3-dB higher in TTS than in SSN for both groups in most conditions (see Table 1). The one exception was the no-plug/msk-side condition for adults, where the average SRT was 3.6-dB *lower* in the TTS than the SSN (-11.7 dB versus -8.1 dB, middle of Figure 2). Recall that in the presence of a simulated UHL, we expected the msk-contra condition to be the most difficult, indicated by higher thresholds, due to the absence of a head-shadow when the masker was on the side of the normal-hearing ear. For both children and adults, the simulated UHL elevated thresholds in SSN by approximately 1 dB in the co-located condition (left panel, Figure 2), 1.3 dB in the msk-ipsi condition, and 6.5 dB in the msk-contra condition (right panel, Figure 2). Larger effects of simulated UHL were seen for the spatially separated target and two-talker masker, where the average effect of simulated UHL was 5.0 dB (child) and 8.4 dB (adult) in the msk-ipsi condition, and 12.3 dB (child) and 14.2 dB (adult) in the msk-contra condition.

Table 1. Mean speech recognition thresholds (SRTs) with and without simulated UHL.

Speech recognition thresholds (SRTs) are in units of dB signal-to-noise ratio (dB SNR). The target and masker were either co-located (co-loc), or the masker was presented from the side (msk-side); in the simulated UHL condition, the masker was presented either ipsilateral (msk-ipsi) or contralateral (msk-contra) to the simulated loss. Standard deviations appear below each mean, in parentheses.

	No plug				**Simulated UHL**					
	Two-talker speech		**Speech-shaped noise**		**Two-talker speech**			**Speech-shaped noise**		
	co-loc	**msk-side**	**co-loc**	**msk-side**	**co-loc**	**msk-ipsi**	**msk-contra**	**co-loc**	**msk-ipsi**	**msk-contra**
Child	1.61*	-6.90*	-3.56*	-7.43	2.28*	-1.92	5.39*	-2.22*	-6.11	0.01*
n = 12	(1.03)	(2.55)	(1.21)	(1.18)	(0.77)	(1.73)	(1.60)	(0.68)	(1.96)	(2.39)
Adult	-0.61*	-11.67*	-4.52*	-8.08	0.83*	-3.27	2.56*	-3.59*	-6.86	-1.97*
n = 11	(1.67)	(2.08)	(0.51)	(0.96)	(0.85)	(1.61)	(1.42)	(0.83)	(1.10)	(1.62)

*Indicates mean difference between children and adults is significant ($p < 0.05$) with Bonferroni adjustment for multiple comparisons.

A rmANOVA analysis of variance was conducted to evaluate the trends observed in Figure 2. There were two levels of masker (TTS, SSN), five levels of listening condition (no-plug/co-loc, no-plug/msk-side, simUHL/co-loc, simUHL/msk-ipsi, simUHL/msk-contra), and two levels of the between-subjects factor of age group (child, adult). Results from this analysis are shown in Table 2. All three main effects reached significance, as did two of the two-way interactions. Of particular importance, the three-way interaction (Masker x Listening Condition x Age Group) was statistically significant. This reflects the fact that the child-adult difference was consistent across listening conditions for the SSN, but not the TTS masker (middle panel, Figure 2). Because of this statistically significant three-way interaction, all lower-order effects should be treated with caution.

Table 2. Results of a repeated-measures analysis of variance (rmANOVA) evaluating the effects of age group, masker, and listening condition on speech recognition thresholds (SRTs).

Results of a repeated-measures analysis of variance (rmANOVA) evaluating the effects of age group (child, adult), masker (TTS, SSN), and listening condition (no-plug/co-loc, no-plug/msk-side, simUHL/co-loc, simUHL/msk-ipsi, simUHL/msk-contra) on SRTs.

Source	***F***	***df***	***p***	**partial η^2**
Age Group	43.04	1, 21	<0.001**	.672
Masker	581.81	1, 21	<0.001**	.965
Listening Condition	224.22	4, 84	<0.001**	.914
Masker x Age Group	26.03	1, 21	<0.001**	.553
Listening Condition x Age Group	1.82	4, 84	0.134	.080
Masker x Listening Condition	69.54	4, 84	<0.001**	.768
Masker x Listening Condition x Age Group	6.00	4, 84	<0.001**	.222

* $p < .05$

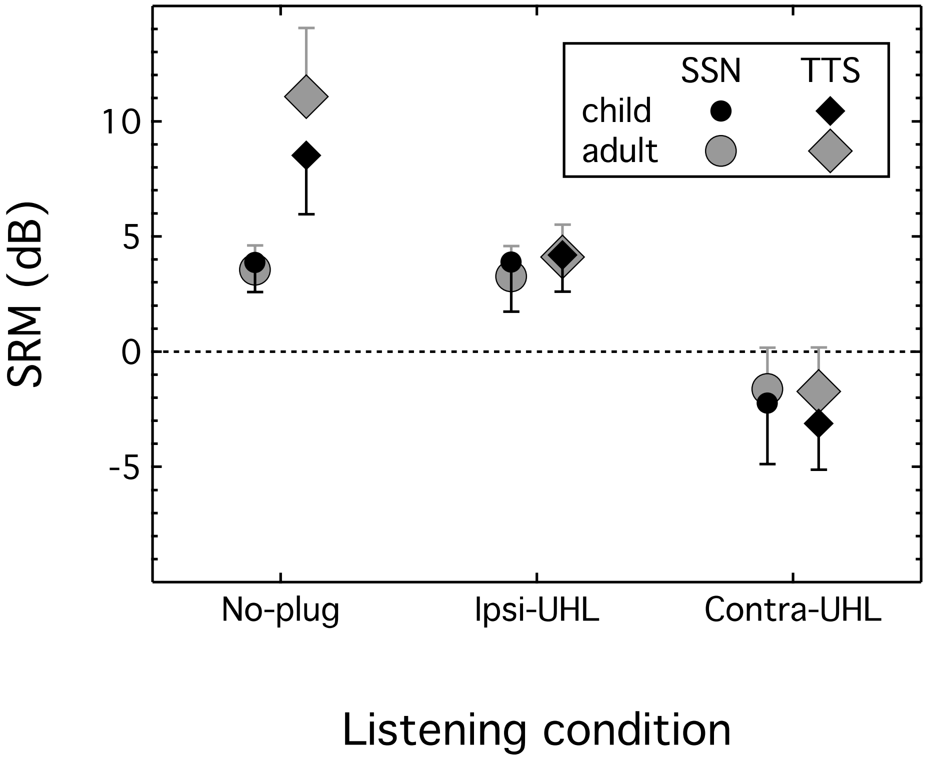
** $p < .001$

Simple main effects testing revealed that SRTs were lower for adults than children in all cases except for the no-plug/msk-side condition in SSN (*p* = 0.169) and the two simUHL/msk-ipsi conditions (*p* = 0.066 and *p* = 0.276 for SSN and TTS, respectively). SRTs were lower for the SSN than the TTS in all cases except the no-plug/msk-side condition for adults (*p* = 0.350). SRTs were significantly lower for the no-plug/co-loc condition than the simUHL/co-loc in all cases except for the child data with the two-talker masker (*p* = 0.208). Significant differences resulting from simple main effects testing are represented in the top panel of Figure 2. Within a given listening condition, a significant effect of masker is indicated by a solid line for children and a dashed line for adults. Stars indicate that children's thresholds are significantly higher than adults' for a given masker and listening condition.

Figure 3 shows the average SRM achieved by children and adults with and without simulated UHL in TTS and SSN. As with Figure 2, circles represent data obtained in SSN, and diamonds represent data obtained in TTS. Symbol shading indicates results obtained from either children (black) or adults (grey). Error bars represent one standard deviation. Positive SRM values indicate better speech recognition performance when the target and masker were spatially separated relative to when they were co-located in azimuth.

Figure 3. Group average spatial release from masking (SRM).

Group average spatial release from masking (SRM, dB) is shown for children and adults with and without simulated UHL in two-talker speech (TTS) and speech-shaped noise (SSN). SRM was calculated as the difference between thresholds obtained when the target and masker were co-located and thresholds obtained when the masker was presented from +90° or -90° on the azimuth. Circles represent SRM achieved in SSN, and diamonds represent SRM achieved in TTS. Symbol shading and size indicate results obtained from either children (small, black) or adults (large, grey). Error bars represent one standard deviation of the mean.



All listeners benefited from spatial separation of target and masker stimuli along the azimuthal plane in the no-plug listening conditions (left third of figure); this benefit was approximately 6-dB larger in the TTS than the SSN masker. In the simulated-UHL listening conditions, a positive SRM was observed only when the masker was presented ipsilateral to the ear with the simulated UHL. This is consistent with the notion that listeners benefitted from head-shadow in the simUHL/msk-ipsi condition. For the SSN, $\mathrm{SRM}_{\text{No-plug}}$ was similar to $\mathrm{SRM}_{\text{Ipsi-UHL}}$, with overall means of 3.7 dB (*SD* = 1.17) and 3.6 dB (*SD* = 1.79), respectively. That is, access to the masker stimulus from the side of the simulated UHL did not increase SRM in the SSN. In contrast, for the TTS, $\mathrm{SRM}_{\text{No-plug}}$ was larger than $\mathrm{SRM}_{\text{Ipsi-UHL}}$, with overall means of 9.7 dB (*SD* = 3.00) and 4.2 dB (*SD* = 1.47), respectively. When the masker was presented contralateral to the simulated UHL, the SRM was -2.5 dB (*SD* = 2.04): that is, when the masker was presented to the ear with better hearing sensitivity, performance was degraded relative to the co-located baseline.

Table 3. Results of a repeated-measures analysis of variance (rmANOVA) evaluating the effects of age group, masker, and listening condition on spatial release from masking (SRM

Results of a repeated-measures analysis of variance (rmANOVA) evaluating the effects of age group (child, adult), masker (two-talker speech, speech-shaped noise), and listening condition (No-plug, Ipsi-UHL, Contra-UHL) on spatial release from masking.

Source	***F***	***df***	***p***	**partial η^2**
Age Group	2.03	1, 21	0.169	.088
Masker	57.99	1, 21	<0.001**	.734
Listening Condition	187.87	2, 42	<0.001**	.899
Masker x Age Group	6.63	1, 21	0.018*	.240
Listening Condition x Age Group	1.51	2, 42	0.233	.067
Masker x Listening Condition	55.42	2, 42	<0.001**	.725
Masker x Listening Condition x Age Group	1.84	2, 42	0.171	.081

* $p < 0.05$

** $p < 0.001$

A rmANOVA was conducted to evaluate the trends in the SRM results shown in Figure 3. There were two levels of masker (TTS, SSN), three levels of listening condition (No-plug, Ipsi-UHL, Contra-UHL), and two levels of the between-subjects factor of age group (child, adult). Results from this analysis are shown in Table 3. There was a significant main effect of masker and a significant main effect of listening condition, but no main effect of age group. There was a significant interaction between masker and listening condition, and between masker and age group; the other interactions failed to reach significance. Simple main effects testing indicates that SRM was larger for TTS than SSN in the No-plug condition (9.7 dB versus 3.7 dB, respectively), but not in the Ipsi-UHL or the Conatra-UHL conditions ($p = 0.181$ and $p = 0.255$, respectively). The SRM within a masker type differed across the three listening conditions in all cases except the No-plug and Ipsi-UHL conditions for SSN ($p = 1.00$). The SRM was significantly different between groups in TTS ($p = 0.015$) but not SSN ($p = 0.835$).

One question of interest is whether the magnitude of attenuation provided in the simulated UHL was associated with the amount of SRM children experienced. Based on the results of Reeder at al. (2015), this association was predicted for attenuation at 500 Hz, but not at the other frequencies. Without correcting for multiple comparisons, the two-tailed bivariate correlation between children's SRM and attenuation values at 500 Hz was statistically significant in the two-talker masker for the Contra-UHL listening condition ($r = -.61$, $p = 0.047$), but not in the other masker conditions ($p \geq 0.283$). Correlations between SRM and thresholds at 1000 and 2000 Hz were not significant. These results are broadly consistent with the idea that attenuation at low frequencies is more detrimental to SRM than attenuation at higher frequencies.

Discussion

The goals of this study were to: 1) determine the effect of an acute simulated UHL on children's SRM in TTS and SSN, and 2) develop a method to be used in future studies that will assess SRM in children who have permanent UHL. The main findings are: 1) SRM is particularly robust in the presence of informational masking for both children and adults with normal hearing, 2) disruption of binaural cues via an acute simulated UHL has different consequences for SRM in the two maskers, and 3) this procedure offers promise for the assessment of SRM in children with permanent UHL. Although it was not the main focus of this study, performance in the co-located conditions will be discussed first because it serves as the baseline condition for quantifying SRM.

Performance in co-located conditions (baseline)

When the target and masker were co-located, performance tended to be better in the no-plug than the simulated-UHL listening conditions. This difference was statistically significant for adults in both maskers and for children in the SSN masker. There was no statistically significant effect of a simulated UHL on children's performance in the co-located two-talker masker. The present results are broadly consistent with previous data comparing performance between no-plug and simulated-UHL conditions for co-located target and masker stimuli. Van Deun et al. (2010) assessed performance with and without a unilateral earplug and earmuff for 8-year-olds and adults on the Leuven Intelligibility Number Test in the presence of speech-weighted noise. Comparing performance with and without the simulated UHL in the co-located target and masker condition, children and adults performed similarly and demonstrated statistically significant binaural summation (average 1.3 dB and 1.4 dB, respectively). For comparison, values of summation in SSN in the present dataset were 1.3 dB for children and 0.9 dB for adults. Mean values of summation in the two-talker masker were 0.7 dB for children and 1.4 dB for adults.

It is not clear how to think about the statistically non-significant summation for children in the two-talker masker. It is possible that summation does not differ across age groups or across maskers, and failure to find a statistically significant effect in the two-talker masker for children is a chance finding. Keep in mind that the summation effects observed in the present dataset were small. However, there is some precedent in the literature for less robust summation in a two-talker masker with a simulated UHL. For example, Marrone et al. (2008) did not observe a statistically significant effect of binaural summation for adults on a closed-set speech recognition task in the presence of same-sex TTS. In that study, adults with normal hearing listened with and without a simulated UHL using a unilateral earplug and earmuff (average attenuation for speech = 38.1 dB). There was a statistically non-significant 0.5-dB difference between SRTs obtained with and without the simulated UHL in the co-located target-masker condition (Marrone et al., 2008).

Summation effects have not consistently been demonstrated in studies of listeners with permanent UHL. We cannot demonstrate summation in listeners with permanent UHL by comparing speech recognition scores when listening with two ears with normal hearing relative to one ear with normal hearing. Rather, summation effects are estimated by comparing performance of listeners with permanent UHL to that of listeners with normal bilateral hearing. Recall that Reeder et al. (2015) examined performance of children with permanent UHL and their peers with normal hearing on a four-alternative forced-choice spondee identification task in the presence of competing speech maskers; data figures suggest only a 0.3-dB summation effect. However, Rothpletz et al. (2012) observed a 4.5-dB summation effect when comparing performance between adults with and without permanent UHL on a speech-on-speech recognition task designed to produce minimal energetic masking. They suggested that adults with normal bilateral hearing have better selective auditory attentional capabilities than adults with permanent UHL (Rothpletz et al., 2012).

Effects of spatial separation

Effects of a simulated UHL on performance in spatially separated maskers are discussed in terms of SRM. Recall that SRM was calculated for three conditions: in the absence of a simulated UHL (SRM), and for maskers positioned ipsilateral or contralateral to the simulated UHL ($\text{SRM}_{\text{Ipsi-UHL}}$ and $\text{SRM}_{\text{Contra-UHL}}$, respectively). As illustrated in Figure 3, SRM tended to decrease with the introduction of a simulated UHL for both children and adults, and for both SSN and TTS. In the TTS conditions, SRM decreased by 5.6 dB when the masker was ipsilateral to the simulated UHL, and by 12.2 dB when it was contralateral. For the SSN conditions, SRM decreased by 5.7 dB when the masker was presented contralateral to the simulated UHL; the effect of simulated UHL was not statistically significant when the masker was ipsilateral to the simulated UHL. In both maskers, children and adults obtained a negative SRM -- worse performance than the co-located baseline -- when the masker was presented contralateral to the simulated UHL.

The magnitude of SRM observed in a relatively steady noise masker for children and adults in the present study is broadly consistent with that found in previous studies. For instance, Van Deun et al. (2010) measured performance on a number recognition task in the presence of speech-weighted noise. Similar to the present study, Van Deun et al. (2010) used an earplug and earmuff to simulate UHL in adults and 8-year-olds with normal hearing. In that study, the SRM was 3.9 dB (children) and 4.0 dB (adults); the $\text{SRM}_{\text{Ipsi-UHL}}$ was 4.2 dB (children) and 4.6 dB (adults). In the present study, the SRM was 3.9 dB (children) and 3.6 dB (adults), and $\mathrm{SRM}_{\mathrm{Ipsi\text{-}UHL}}$ was 3.9 (children) and 3.3 dB (adults). Considering the difference in task difficulty (number recognition versus open-set sentence recognition) and differences in methodology between the two studies, our results are in line with those reported by Van Deun et al. (2010).

The values of SRM observed for adults in the two-talker masker can also be compared with those obtained in other studies using maskers associated with informational masking. Rothpletz et al. (2012) measured SRM for adults using the Coordinate Response Measure (CRM; (Bolia, Nelson, Ericson, & Simpson, 2000) paradigm in a single-talker speech masker. The CRM paradigm is a closed-set speech recognition task. In the single-talker masker, the CRM is sensitive to informational masking (e.g., Brungart, 2001). To further minimize energetic and maximize informational masking, Rothpletz et al. (2012) digitally processed the target and masker speech to minimize spectral overlap between the target and masker stimuli. Similar to the present study, target speech was always presented from 0° azimuth, and the masker was presented from 0°, +90°, or -90° azimuth. They found that adults with permanent UHL achieved 3.9 dB SRM when the single-talker masker was presented ipsilateral to the ear with UHL, and -2.5 dB SRM when it was presented contralateral to the ear with UHL. Adults with simulated UHL in the present study achieved 4.1 dB SRM when the two-talker masker was presented ipsilateral to the ear with UHL ($\mathrm{SRM}_{\mathrm{Ipsi\text{-}UHL}}$) and -1.7 dB SRM when it was presented contralateral to the ear with simulated UHL ($\mathrm{SRM}_{\mathrm{Contra\text{-}UHL}}$).

As discussed in the Introduction, there are few studies of masked speech recognition or SRM in children with permanent or simulated UHL using maskers associated with informational masking. The most relevant comparison can be made between our results and those obtained by Reeder et al. (2015). As a reminder, Reeder et al. (2015) assessed performance of 7- to 16-year-olds with moderately-severe to profound sensorineural UHL on a range of speech recognition tasks. One of their tasks assessed masked spondee recognition in single-talker male and female maskers as well as in multi-talker babble presented from 0°, +90°, or -90° azimuth. To maximize stimulus uncertainty, thereby increasing informational masking, masker presentation was pseudorandomized for each spondee presentation. Although SRM was not calculated on the spondee recognition task, data figures are consistent with an SRM of 9 dB for children with normal hearing. This is similar to 8.5-dB SRM observed for children in the present study in the two-talker masker. For children with permanent UHL, SRM in the Reeder at al. (2015) study was 7 dB when the masker was ipsilateral to the UHL and 0 dB when the masker was contralateral to the UHL. In contrast, children with simulated UHL in the present study achieved an SRM of 4.2 dB when the masker was ipsilateral to the simulated UHL ($\text{SRM}_{\text{Ipsi-UHL}}$) and -3.1 dB when the masker was contralateral to the simulated UHL ($\text{SRM}_{\text{Contra-UHL}}$). One challenge in comparing the present results with those of Reeder et al (2015) is that values of SRM based on those published data represent average performance in each of three maskers -- single male talker, single female talker, and multi-talker babble -- whereas the present study used a two-talker masker. Another consideration is that the masker was unpredictable from interval to interval in the study of Reeder et al. (2015); the resulting stimulus uncertainty could have increased informational masking. It is therefore difficult to compare the relative influence of informational masking on the results obtained across the two studies.

Effect of masker on spatial release from masking

Based on previous data, it was predicted that the benefit of spatially separating the target and masker would be larger for the TTS relative to the SSN masker, due to greater informational masking with the two-talker masker. It is often argued that spatial separation of target and masker stimuli facilitates auditory stream segregation. When tested without the earplug, both children and adults achieved more SRM in the TTS than the SSN masker. In the no-plug condition, SRM for the two maskers differed by 4.6 dB for children and 7.5 dB for adults. These results are consistent with data from previous studies showing that listeners achieve greater SRM on a speech recognition task in the presence of competing speech than competing noise (e.g., Arbogast et al., 2002; Arbogast, Mason, & Kidd, 2005; Freyman et al., 2001, 2004, 1999; Johnstone & Litovsky, 2006). For instance, Freyman et al. (1999) measured adults' speech recognition for syntactically correct, nonsense sentences in the presence of speech-spectrum noise or competing single-talker speech. The target and competing speech were both produced by female talkers. Target speech was always presented from the front of the listener (0° azimuth), and the competing noise or speech was presented from +60° azimuth. The SRM was 8 dB for the speech-spectrum noise compared with 14 dB for the single-talker speech masker (Freyman et al., 1999).

In contrast to the no-plug data, the masker type did not affect SRM in the simulated UHL conditions for children or adults. The SRM for both children and adults in TTS and SSN was approximately 4 dB when the masker was presented ipsilateral to the simulated UHL, and approximately -2 dB when the masker was presented contralateral to the simulated UHL. Comparing SRM in the simulated UHL and no-plug conditions suggests that the availability of binaural cues has very different consequences for the two maskers. In SSN, introducing a simulated UHL ipsilateral to the masker has no effect on SRM. This observation is consistent with the idea that improved SNR in the ear contralateral to the masker (head shadow) is responsible for SRM in SSN. In contrast, introducing the TTS masker ipsilateral to the UHL reduces SRM from 8.5 dB to 4.2 dB in children, and from 11.1 dB to 4.1 dB in adults. These results suggest that the benefit of access to binaural cues cannot be attributed entirely to the head shadow effect when the masker is TTS. The benefit of access to cues available in the ear ipsilateral to the masker is sometimes described as squelch. The different mix of binaural cues contributing to performance in the two maskers could be related to relative contributions of informational masking in the baseline condition, where the target and masker are co-located; TTS is thought to introduce substantially more informational masking than SSN. The present results are therefore consistent with the idea that squelch plays an important role for speech recognition in an informational masker, but little to no role in an energetic masker.

Child-adult differences in SRM for the two-talker masker

The final prediction was that adults would benefit more than children from binaural cues when the target and two-talker masker were spatially separated. We expected this age effect to be most evident in the no-plug conditions since listeners would have full access to the binaural cues that support SRM. Results are consistent with the idea that children obtain a smaller SRM than adults when the target is spatially separated from the TTS. While there was no three-way interaction in the analysis of SRM, the largest mean difference between SRM for children and adults (2.6 dB) was observed for the two-talker masker in the no-plug/msk-side condition; in contrast, the child-adult difference ranged from 1.4 to -0.6 dB in the other five test conditions.

There is no consensus on the developmental trajectory of SRM in children. Studies from Litovsky and colleagues have concluded that children as young as 3 years of age show adult-like SRM on masked speech recognition tasks in the presence of competing speech or noise (e.g., Garadat & Litovsky, 2007; Litovsky, 2005). However, other studies suggest that development of SRM is not complete until adolescence (e.g., Cameron, Dillon, & Newall, 2006a, 2006b). For instance, Yuen and Yuan (2014) measured SRM on the Mandarin Pediatric Lexical Tone and

Disyllabic Word Picture Identification Task in Noise (MAPPID-N) in adults and 4.5- to 9-year-olds. The MAPPID-N is a closed-set forced-choice speech recognition task utilizing SSN as the masker. Children achieved approximately 3-dB less SRM than adults on the disyllabic word subtest and approximately 4-dB less SRM than adults on the lexical tone subtest. Importantly, regression analyses on the child data suggest that children's SRM significantly improved with age on both subtests, and that age accounted for 32-34% of the variance in children's SRM.

The psychoacoustic literature provides additional support for the idea that SRM is immature for school-age children when tested using an informational masker. Specifically, that literature indicates that children may not process binaural cues as efficiently as adults under some conditions. One way to measure the binaural auditory system's sensitivity to interaural time and level differences is the masking level difference (MLD; Grose et al., 1997; Hirsh, 1948). The MLD is estimated by measuring thresholds in two conditions: with the target and masker presented diotically and with those stimuli presented dichotically. The difference in thresholds for these two conditions is the MLD. For narrowband maskers, the MLD is smaller for school-age children than adults (Grose et al., 1997). This child-adult difference is thought to reflect children's inability to use the interaural difference cues to capitalize on stimulus cues present in the masker envelope minima (Hall, Buss, Grose, & Dev, 2004). Immaturity in the ability to use binaural cues in a narrowband masker may reflect the same limitations as observed in the two-talker masker of the present dataset. For instance, children's immature ability to use binaural cues to capitalize on target speech cues in the fluctuating two-talker masker could have contributed to the observed child-adult difference in SRM for that masker in the present data.

Extent of simulated UHL

Average degree of simulated UHL. There is precedent for a correlation between SRM and low-frequency hearing thresholds for children with UHL. Reeder et al. (2015) reported that children with lower (better) thresholds in their normal-hearing ear at 500 Hz had lower (better) adaptive SRTs when competing single-talker male or female speech was spatially separated to the side of their normal-hearing ear ($r = 0.71$, $p < 0.05$); this association was not observed with multi-talker babble. Reeder et al. (2015) suggested that even a minimal difference in hearing sensitivity is important for binaural processing. Without correcting for multiple comparisons, the two-tailed bivariate correlation between children's $\text{SRM}_{\text{Contra-UHL}}$ in the two-talker masker and attenuation values at 500 Hz in the present dataset was statistically significant ($r = -0.61$, $p \leq 0.05$); this was the only statistically significant correlation. This result suggests that, as degree of simulated UHL increased at 500 Hz, children benefited less from spatial separation of the two-talker masker when it was spatially separated to the side of their normal-hearing ear. A parallel analysis was not performed on adult data because speech data and attenuation values were collected from different individuals in all but two cases. An association between low-frequency simulated UHL and SRM is also broadly consistent with the results of Noble et al. (1994), who reported that, as degree of low-frequency conductive hearing loss increased, localization performance in the horizontal plane decreased. Similar results for SRM would be predicted to the extent that SRM relies on the same binaural cues as localization.

One limitation of the present protocol is that attenuation was only measured at 500, 1000, and 2000 Hz. While attenuation values for adults and children were largely comparable across this range, we cannot rule out the possibility that attenuation differed between groups above 2000 Hz or below 500 Hz.

Acute versus chronic UHL. A goal of the present study was to examine the effects of an acute simulated UHL on SRM, as a preliminary step towards developing methods of assessing SRM in children with long-standing UHL. There is evidence to suggest that the auditory system adapts to disrupted binaural input over time (Kumpik et al., 2010). For instance, Kumpik et al. (2010) investigated the effect of training on free-field localization of flat-spectrum or random-filtered noise stimuli in adults with normal bilateral hearing who had an earplug placed in one ear. Relative to the no-plug condition, placement of a unilateral earplug significantly reduced localization performance from ≥85% correct to ≤50% correct. Adults who received localization training with the unilateral earplug for 7-8 days showed significant improvement in free-field localization abilities for flat-spectrum noise. These results suggest that the auditory system can adapt to disrupted binaural input by reweighting localization cues (Kumpik et al., 2010). However, Kumpik et al. (2010) did not see evidence of adaptation within a single test session. Further evidence that adaptation to disrupted binaural input does not occur within a single test session comes from Slattery and Middlebrooks (1994). In that study, adults with normal bilateral hearing completed a localization task in the presence of a unilateral earplug and earmuff. Performance was assessed immediately after placing the earplug and after 24-hrs experience wearing the earplug; the earmuff was placed over the earplug only during testing. Performance on the localization task did not differ between the two time points. It is likely that results from the present study would be different had the listeners acclimatized to listening with the simulated UHL over a period longer than 24 hrs.

Conductive versus sensorineural hearing loss. There are important differences between the impacts of conductive versus sensorineural hearing loss that should be considered when interpreting our data. In the present study, we simulated a conductive UHL by occluding one ear with an earplug and earmuff. Conductive hearing loss results in attenuation of air-conducted auditory stimuli, while sensorineural hearing loss results in attenuation and distortion of air-conducted auditory stimuli (Dreschler & Plomp, 1980, 1985; Glasberg & Moore, 1988; Plomp, 1978). In adults with moderate hearing loss, symmetrical conductive hearing loss is relatively more detrimental to sound source localization in the horizontal plane than symmetrical sensorineural hearing loss (Noble, Byrne, & Lepage, 1994). This performance difference has been attributed to disruption of low-frequency interaural time cues in listeners with conductive hearing loss. For listeners with conductive hearing loss, reduced effectiveness of air conducted sound and increased reliance on bone conduction leads to a loss or reduction of cochlear isolation (Noble et al., 1994) and consequent reduction of binaural difference cues. This is relevant to the current study because SRM and localization are thought to rely on some of the same binaural cues. The distortion of air-conducted sound in sensorineural hearing loss and the disruption of bone-conducted interaural cues in conductive hearing loss may affect SRM in ways that are not captured by the simulated conductive UHL evaluated in the present study. This possibility will be addressed in future studies of children with permanent conductive and sensorineural UHL.

Conclusions

Overall, our findings confirm that children and adults with normal bilateral hearing experience greater SRM for primarily informational as opposed to energetic masking. Given that the effect of masker type on SRM was essentially eliminated in the presence of a simulated UHL, these results suggest that the detriment of listening with disrupted binaural input is more evident in competing TTS than SSN for both children and adults. This was a first step towards applying this method of testing to children with permanent UHL. We expect that listeners with permanent UHL will experience some of the same deficits that listeners with simulated UHL demonstrated on the present task. However, we expect that degree and type of hearing loss and the adoption of compensatory listening strategies could impact the results obtained in listeners with permanent UHL. The present data suggest that even mild to moderate degrees of conductive hearing loss may eliminate SRM and potentially result in functional communication difficulties. The finding that binaural squelch plays an important role in SRM for competing TTS, but not SSN, could also have implications for audiologic rehabilitation and preferential classroom seating. Specifically, some children may benefit from more aggressive audiologic treatment options in the presence of competing speech. Given the association between speech recognition performance in a two-talker masker and children’s real-world listening difficulties (Hillock-Dunn et al., 2015), assessment of SRM in a two-talker masker may provide important insight into the difficulties children with UHL face in their everyday environments, such as classrooms.

CHAPTER 3: SPATIAL HEARING AND FUNCTIONAL AUDITORY SKILLS IN CHILDREN WITH UNILATERAL HEARING LOSS

Introduction

It is well documented that children with unilateral hearing loss (UHL) are at increased risk for difficulties in a variety of developmental domains, including academic, behavioral, cognitive, language, social-emotional, and speech (Bess & Tharpe, 1986; Bovo et al., 1988; Culbertson & Gilbert, 1986; Ead et al., 2013; Jensen et al., 1989; Lieu, 2004; Lieu et al., 2013, 2012; McKay et al., 2008; Oyler et al., 1988; Porter et al., 2013; Tharpe, 2008). One explanation for these deficits is that children with UHL have reduced access to binaural difference cues, or differences in the spectral, intensity, and temporal profiles of sound at the two ears, which are critical for spatial hearing. Spatial hearing broadly refers to the ability of the auditory system to use the distinctive paths by which sounds travel from their sources to get a sense of the soundscape (Blauert, 1997). Because spatial hearing facilitates localization and unmasking of, as well as orientation to, sound sources, it is critical for safety and optimal speech recognition in the complex listening environments where development occurs (i.e., home, daycare, school). Few studies have investigated the specific nature of the spatial hearing deficits that children with UHL experience. Defining this population's spatial hearing deficits is critical for understanding and remediating the factors that contribute to the marked differences in developmental outcomes observed among children with UHL. The present study evaluates the consequence of pediatric sensorineural UHL on three auditory measures that rely heavily on binaural hearing, and may consequently highlight different aspects of this population's spatial hearing deficits: (1) sound source localization, (2) spatial release from masking, and (3) functional listening abilities as assessed by parent report.

In complex, multi-source environments, sounds emanate from different locations around a listener. Sounds that originate from different locations on the azimuthal plane will arrive at different times and with different intensities at the two ears (Blauert, 1982; Brungart & Rabinowitz, 1999). These interaural differences in time and level are collectively known as binaural difference cues. Given the physics of how sounds interact with a listener’s head and torso, interaural time differences (ITDs) are greatest for signals below 1500 Hz, while interaural level differences (ILDs) are greatest for signal frequencies above 1500 Hz (Blauert, 1997). As a result, ITDs are the primary determinant of source location for low-frequency sounds, while ILDs are the predominant determinant of source location for high-frequency sounds (Nordlund, 1962; Stevens & Newman, 1936; Strutt, 1907; Wightman & Kistler, 1992). Sounds originating from different locations on the vertical and azimuthal planes will interact with the anatomy of each ear independently, giving rise to monaural spectral shape cues. Monaural spectral shape cues, also referred to as pinna cues, arise from the direction-dependent modifications of incoming sound that result from the filtering of each ear (Batteau, 1967; Blauert, 1969; Gardner & Gardner, 1973; Kistler & Wightman, 1992; Shaw, 1974). These cues are strongest above about 3800 Hz, and by definition do not require a comparison of signals between the two ears (Hebrank & Wright, 1974; Wightman & Kistler, 1992). Monaural spectral shape cues may be used to resolve sound source locations when binaural difference cues are ambiguous (Irving & Moore, 2011; Van Wanrooij & Van Opstal, 2004). As a result, monaural spectral shape cues are most commonly associated with localization on the vertical plane (Irving & Moore, 2011; Van Wanrooij & Van Opstal, 2007; Wightman & Kistler, 1992, 1997). In listeners with normal hearing (NH), spatial hearing is dominated by reliance on binaural cues (Best, van Schaik, & Carlile, 2004; David, Grimault, & Lavandier, 2015; Macpherson & Middlebrooks, 2002; Middlebrooks & Onsan, 2012; Schwartz, McDermott, & Shinn-Cunningham, 2012; Wightman & Kistler, 1992). It is therefore not surprising that listeners with UHL demonstrate difficulties on spatial hearing tasks such as sound source localization and speech recognition in multi-source environments.

Sound source localization in quiet

Children with UHL are deprived of typical binaural difference cues, and are thus at a disadvantage for localizing sounds on the azimuthal plane. Several studies have shown that children with UHL demonstrate a wide range of localization abilities (Bess et al., 1986; Bovo et al., 1988; Humes et al., 1980; Johnstone, Nábělek, & Robertson, 2010; Newton, 1983). In fact, some listeners with UHL localize sounds nearly as well as their peers with NH (Reeder et al., 2015). A similar trend has been observed for adults with UHL (Agterberg, Hol, Van Wanrooij, Van Opstal, & Snik, 2014; Agterberg, Snik, Hol, Van Wanrooij, & Van Opstal, 2012; Firszt, Reeder, Dwyer, Burton, & Holden, 2015; Rothpletz et al., 2012; Slattery & Middlebrooks, 1994; Van Wanrooij & Van Opstal, 2004, 2007). This suggests that listeners with UHL may learn to use monaural spectral or degraded binaural difference cues for sound source localization on the azimuthal plane (Newton, 1983; Slattery & Middlebrooks, 1994).

The most compelling results regarding the use of monaural spectral shape cues to sound source localization by children with UHL come from Newton (1983), who assessed the localization abilities of 22 children, 10 to 16 years of age, with severe-to-profound UHL, tested with and without access to pinna cues. In that study pinna cues were eliminated by covering the pinna on the side of the better-hearing ear. For some children with UHL, performance with access to pinna cues was similar to that of children with NH. In those cases, covering the pinna had a large detrimental effect; that result was interpreted as indicating that performance in the uncovered condition reflected the use of spectral cues for localization. Somewhat surprisingly, the localization performance of children with UHL who performed similarly to their peers with NH was not correlated with the duration of UHL (Newton, 1983). Similar results have been obtained in adults with severe-to-profound UHL (Agterberg et al., 2014, 2012; Firszt et al., 2015; Van Wanrooij & Van Opstal, 2004). Additionally, the localization abilities of better-performing adults with UHL are correlated with the high-frequency hearing of their better-hearing ear (Agterberg et al., 2014; Firszt et al., 2015). Overall, these findings suggest that the marked variability of localization abilities observed among listeners with UHL may be partly attributed to their use of monaural spectral shape cues.

While previous studies have investigated the extent to which children with UHL can localize 500 Hz and 3000 Hz tones (Bess & Tharpe, 1986; Bess et al., 1986; Bovo et al., 1988; Humes et al., 1980; Newton, 1983), high-pass filtered noise (Newton, 1983), and words (Johnstone et al., 2010; Reeder et al., 2015), there has been no systematic investigation into the relative contributions of binaural difference and monaural spectral shape cues to sound source location in children with UHL. Results from such an investigation would be critical for tailoring intervention efforts to address individual needs. Subsequently, the extent to which listeners with UHL rely on ITDs, ILDs, and monaural spectral shape cues for sound source localization on the azimuthal plane was indirectly examined in the present study. Broadband stimuli were filtered to create signals that contained strong ITD cues and minimal ILD cues, strong ILD cues and minimal ITD cues, or unpredictable spectral content (Dorman et al., 2015).

Spatial release from masking

Spatial separation of target and masker stimuli on the azimuthal plane improves masked speech recognition for listeners with NH; this benefit is called spatial release from masking (SRM; Bronkhorst & Plomp, 1992). The magnitude of SRM is often expressed as the difference between speech recognition thresholds (SRTs) obtained in two conditions -- one in which target and masker sounds originate from the front of the listener, and another in which the target sound is in front of the listener and the masker sound is offset to the side of the listener. In listeners with NH, SRM is pronounced for unpredictable stimuli and when target and masker stimuli are perceptually similar (Arbogast et al., 2002; Freyman et al., 2001; Hawley et al., 2004; Johnstone & Litovsky, 2006; Misurelli & Litovsky, 2015). The large SRM observed for these stimuli is likely driven by the increased challenge of segregating target from masker stimuli when spatial cues are absent (i.e., in the co-located condition; Arbogast et al., 2002; Brungart, 2001; Freyman et al., 2001; Hawley et al., 2004). For speech-on-speech recognition, informational masking is relatively high in the presence of 2–3 competing talkers of the same sex as the target talker (Freyman et al., 2004; Rosen, Souza, Ekelund, & Majeed, 2013).

As a result of absent or distorted binaural difference cues, permanent or simulated hearing loss of any degree is associated with speech perception deficits and reduced benefit of target-masker separation (Bess et al., 1986; Bovo et al., 1988; Gallun, Diedesch, Kampel, & Jakien, 2013; Glyde et al., 2015; Griffin, Poissant, & Freyman, 2018; Jensen et al., 1989; Marrone et al., 2008; Reeder et al., 2015; Rothpletz et al., 2012; Ruscetta et al., 2005). It has become increasingly evident that the detrimental effect of UHL on adults in these contexts is striking under conditions associated with high levels of informational masking (Marrone et al., 2008; Rothpletz et al., 2012). However, there have been very few systematic investigations of masked speech perception or SRM in the context of low versus high informational masking for children with simulated or permanent UHL (Corbin, Buss, & Leibold, 2017; Griffin et al., 2018; Reeder et al., 2015). This represents a critical gap in the literature given that the speech perception difficulties experienced by children with bilateral hearing loss are not only exacerbated in the presence of informational masking, but performance with these maskers is representative of their performance in realistic listening environments outside the confines of the audiology booth (Hillock-Dunn et al., 2015; Leibold et al., 2013). It is important to assess speech recognition abilities and SRM in children with UHL under conditions associated with informational masking, given the importance of binaural hearing for performance on such measures.

Reeder and colleagues (2015) investigated speech perception abilities of children with UHL and age-matched peers with NH under multiple spatial conditions in the presence of four-talker babble, diffuse restaurant noise, single-talker speech, or multi-talker speech. The overall group differences were similar across the different maskers. While this could indicate that children with UHL are not at a greater disadvantage for informational masking in competing speech, that study did not assess performance under conditions for which informational masking is maximal -- in a masker composed of 2 to 3 competing talkers. Subsequently, Corbin et al. (2017) compared SRM for competing speech from two talkers of the same sex and speech-shaped noise (SSN) in 8- to 10-year-olds with bilaterally NH in two conditions: with and without a simulated UHL (see Chapter 2). Target sentences were always presented from the front of the participant (0°), while the masker was presented from 0°, +90°, or -90°. Corbin et al. (2017) found that the detriment of simulated UHL was larger in two-talker speech (TTS) relative to SSN. Most recently, Griffin et al. (2018) compared SRM for TTS and SSN between children with permanent sensorineural UHL and children with NH. Similar to Corbin et al. (2017), Griffin and colleagues (2018) observed a greater performance difference in SRTs between children with UHL and children with NH in the TTS relative to the SSN.

Functional listening abilities

Evidence suggests that auditory handicap is significantly affected by spatial hearing abilities (Gatehouse & Noble, 2004; Noble & Gatehouse, 2006). Broadly, auditory handicap refers to the disadvantage experienced by an individual during typical daily activities as a result of hearing impairment (World Health Organization, 1980). It is therefore not surprising that listeners with UHL report the most listening difficulties in everyday environments where spatial hearing is critical to performance, such as when trying to understand speech in the presence of competing talkers or segregating and determining the location of sound sources (Dwyer, Firszt, & Reeder, 2014; Gatehouse & Noble, 2004; Noble & Gatehouse, 2004, 2006). Asymmetric hearing, defined as bilateral hearing loss with an average difference between ears of greater than 10 dB for the pure-tone average at 500, 1000, 2000, and 4000 Hz, has also been linked to a reduced ability to segregate signals and an increased effort to engage in conversation (Dwyer et al., 2014; Noble & Gatehouse, 2004; Olsen, Hernvig, & Nielsen, 2012). When hearing sensitivity is statistically controlled, adults' self-rated performance on spatial hearing tasks such as those just described is more closely related to auditory handicap than traditional measures of speech perception in noise (Gatehouse & Noble, 2004; Phatak, Brungart, Zion, & Grant, 2018; Swaminathan et al., 2015). It makes sense that a similar relationship between spatial hearing ability and real-world listening difficulty would apply to children with hearing loss. However, the spatial hearing abilities of children with UHL are rarely assessed in the audiology clinic. Such comparisons could elucidate the factors responsible for the sizeable performance differences among individual children with UHL that are not explained by the audiogram or conventional diotic speech-in-noise testing involving steady noise or multi-talker babble.

In the present study, the relationship between SRM and parents' reports of their children's real-world listening abilities was assessed using the Ease of Communication and Background Noise subscales of the Parent's Version of the Abbreviated Profile of Hearing Aid Performance (APHAP; Kopun & Stelmachowicz, 1998), as well as the Speech, Spatial, Qualities Scale for Parents of children with hearing loss (SSQP; Galvin & Noble, 2013). It was predicted that SRM in the TTS masker would be related to parent's ratings of their children's listening abilities on the APHAP and SSQP. The rationale for this prediction was: (1) binaural hearing supports SRM in competing speech composed of a small number of talkers, (2) many questions on the APHAP and all questions on the SSQP assess communication abilities in listening situations enhanced by binaural hearing, and (3) SRM in informational masking is reflective of real-world listening.

Purpose of the study

The overall purpose of this study was to better understand the spatial hearing abilities of children with UHL. Localization of sounds on the azimuthal plane was assessed with filtered and spectrally unpredictable stimuli in order to better characterize the extent to which children with UHL make use of binaural difference and/or monaural spectral shape cues. Masked speech recognition and SRM was evaluated to quantify the spatial hearing deficits experienced by children with UHL. Performance was assessed in TTS and SSN, to evaluate the effect of masker type. In light of data suggesting that susceptibility to informational masking in TTS is correlated with the real-world communication abilities of children with bilateral hearing loss (Hillock-Dunn et al., 2015), this represents an important first step towards understanding this population's performance in everyday environments. For children with UHL, the relationship between masked speech recognition and parental report of situational listening abilities was examined. Findings from the present investigation could provide a basis for our understanding of the deficits and individual differences observed in this population.

Materials and Methods

Participants

Data were collected from 15 children with permanent UHL (ages 5.3 to 14.9 years, 9 females), 15 children with NH matched for age (±6 months) and sex (male/female) to the children with UHL, and 15 adults with NH (ages 22 to 30 years). This cohort of participants was different from that described in Chapter 2; all participants were naïve to the experimental protocol. Participants with NH were recruited from The University of North Carolina at Chapel Hill (UNC) community and surrounding area. Children with UHL were recruited through audiologist referral and review of electronic health records at the UNC Health Care Pediatric Audiology Program, in addition to word-of-mouth from local audiology clinics. Consent and/or assent to participate in the present study was obtained prior to any experimental testing. This research was approved by the Institutional Review Board of UNC.

Inclusion criteria for all participants were: (1) native English-speaking; (2) healthy on the day of testing; and (3) pass a tympanometric screening, except for ears with previously diagnosed conductive or mixed hearing losses (equivalent ear canal volume 0.3 cm^3–2.0 cm^3, tympanometric peak compliance 0.2–1.4 cm^3, tympanometric peak pressure -200 to +100 daPa, gradient 50–150 daPa). Exclusion criteria for all participants were: (1) developmental disorder comorbid with hearing loss; (2) treatment for otitis media within one week prior to testing; and (3) ≥3 episodes of otitis media within the previous 3 years. Two children did not pass the tympanometric screening: one child with NH and one child with UHL. The child with NH was excluded from the study. The child with UHL failed the tympanometric screening due to the presence of a patent pressure equalization (PE) tube in the better-hearing ear. Given that this child's pure tone air- and bone-conduction thresholds in the better-hearing ear were within the range of NH and unaffected when compared to previous audiometric evaluations, she completed the research testing protocol and her data were included (UHLf).

Participants with NH had pure-tone air-conduction thresholds of ≤20 dB HL at octave frequencies 250–8000 Hz, bilaterally (American National Standards Institute, 2010). Children with UHL had one ear with NH and one ear with permanent sensorineural or mixed hearing loss. The definition of UHL used in this study was adapted from that put forth in the national proceedings of the 2005 National Workshop on Mild and Unilateral Hearing Loss (National Workshop on Mild and Unilateral Hearing Loss: Workshop Proceedings, 2005). Specifically, permanent UHL was indicated by an average pure-tone air conduction threshold at 500, 1000, and 2000 Hz of ≥20 dB HL or pure-tone air conduction thresholds >25 dB HL at two or more frequencies in the range of 3000–8000 Hz in the affected ear, with an average pure-tone air conduction threshold in the better-hearing ear ≤20 dB HL. Table 4 provides details regarding the audiometric characteristics of the participants with UHL. Two children did not meet the strict criteria for UHL, displaying asymmetric hearing loss, with either a PTA >20 dB HL (UHLm) or thresholds increasing from 25 dB HL at 4000 Hz to 50 dB HL at 8000 Hz in the better-hearing ear (UHLp).

Table 4. Audiometric and demographic data for children with UHL.

Participant ID	Age (years)	Sex	Side of UHL	PTA, side of UHL	Unaided SII at 75 dB SPL	Onset	Pass/Fail UNHS L/R	Presumed Etiology	Device (usage, per data logging)
UHLa	5.3	M	L	NR	0	C	Unknown	Slight enlargement of left vestibule	none
UHLb	5.3	M	R	105	0	A	Unknown	Unknown	none
UHLc	5.9	F	L	115	0	C	Unknown	CMV	Desktop FM
UHLd	6.2	F	R	43	81	A	P/P	Unknown*	Phonak Sky Q70-M13 (5.6 hrs/day)
UHLe	6.5	F	L	72	2	C	R/P	Absence of 8th nerve cochlear branch[&]	none
UHLf	6.7	F	R	25^{+}	72	A**	Unknown	Unknown	Phonak Sky V70-P (7.9 hrs/day)
UHLg	7.1	M	R	NR	0	A	P/P	Unknown*	none
UHLh	7.6	F	L	60	26	A	P/P	Unknown^ jaundice	History of ear-level FM
UHLi	8.0	F	L	53	35	A	P/P	Mild cochlear dysplasia w/ enlargement of endolymphatic sac	Desktop FM
UHLj	9.1	F	L	23^{+}	84	C	P/P	Unknown[#]	Soundfield FM
UHLk	9.1	F	L	NR	0	A	P/P	Viral illness	none
UHLm	9.4	M	L	48	73	A	Unknown	Otosclerosis*	Personal FM Phonak Sky Q70-M13 (6.8 hrs/day)
UHLn	9.7	F	R	70	2	A	P/R	Unknown	None
UHLo	11.5	M	R	100	0	A	Unknown	Right EVA and mild cochlear dysplasia	Soundfield FM Phonak CROS H2O (NA) Phonak Sky Q50 M13 (NA)
UHLp	14.9	M	R	103	0	A	Unknown	Bilateral EVA	Phonak Sky V 70 P BiCROS (NA)

The pure tone average (PTA) was calculated using air-conduction audiometric thresholds at 500, 1000, and 2000 Hz.

Unaided Speech Intelligibility Index (SII) is shown for the worse-hearing ear.

**= UHL could have been congenital but not identified via Universal Newborn Hearing Screening conducted with automated Auditory Brainstem Response due to the reverse cookie-bite configuration

[+] = UHL based on two or more pure tone air-conduction thresholds greater than or equal to 25 dB HL at > 2000 Hz

[^] = At least one Joint Committee on Infant Hearing (JCIH) high-risk indicator

* = significant family history

[#] = born w/right periorbital hemangioma

[&]= absence of cochlear branch of the 8th nerve on imaging; previous audiologic reports indicate an ABR consistent with auditory neuropathy/dysynchrony and pure tone air-conduction responses in the severe-profound hearing loss range

A = acquired

C = congenital

M = male

F = female

CROS = Contralateral Routing of Offside Signal

FM = frequency-modulation system

EVA = Enlarged Vestibular Aqueduct Syndrome

R = right

L = left

UNHS = Universal Newborn Hearing Screening

All but two children with UHL had an audiogram completed within the previous 6 months by their primary audiologist. Audiometric thresholds in the affected ear of children with UHL who had recent audiograms on file were documented as stable within the previous year. For the two children with UHL who did not have a recent audiometric evaluation on file, pure-tone air- and bone-conduction testing was undertaken with appropriate masking levels by a licensed pediatric audiologist in the lab. In both cases, the results obtained were consistent with sensorineural UHL as documented in their electronic health record. While we attempted to recruit a cohort of children with a range of UHL severity, the majority of children with UHL in this study had severe to profound UHL. The unaided Speech Intelligibility Index (SII; ANSI, S3.5-1997) was used to represent the audibility of a standard speech stimulus presented at 75 dB SPL in the unaided ear with UHL. The SII was calculated using the Verifit2 Audioscan (Audioscan) and is represented in the present study as the percentage of speech cues in the standard speech stimulus that is available to the listener based on their pure-tone audiometric thresholds. As seen in Table 4, only six children with UHL possessed unaided SII values greater than 5 in this study. Three participants with UHL were consistent users of a hearing aid in the affected ear, and two used Contralateral Routing of Off-Side Signal (CROS) systems. One child (UHLo) reported inconsistent use of the CROS system.

Four of the five children with UHL who used a hearing aid or CROS returned to the lab to complete the experimental protocol with their personal hearing device (UHLd, UHLf, UHLm, and UHLp). Prior to experimental testing, hearing aids were verified with simulated real-ear measures. Individual real-ear-to-coupler differences were measured and incorporated in the verification procedure. All hearing aids matched DSL v5.0a child prescriptive targets for gain at 65 dB SPL using a standard speech passage on the Audioscan Verifit. Probe-microphone measures were used to verify that the CROS system was operating and appropriately transmitting the auditory signal from the poorer-hearing to the better-hearing ear (Pumford, 2005).

There is precedent in the literature to suggest that children with UHL have poorer receptive language skills than their peers with NH (Cozad, 1977; Klee & Davis-Dansky, 1986; Lieu et al., 2010; Porter et al., 2013). This is an important group difference because vocabulary size is known to affect speech recognition in children with hearing loss (Klein, Walker, Kirby, & McCreery, 2017). To characterize the receptive vocabularies of children who participated in the present study, the Peabody Picture Vocabulary Test-IV (PPVT; Dunn & Dunn, 2007) was administered. In our study cohort, there was a significant difference in PPVT standard scores between children with NH (M = 124.3, SD = 13.4) and children with UHL (M = 111.8, SD = 18.3); $t(28) = -2.12$, p = 0.043. This difference, however, should be interpreted with caution. With the exception of one child with UHL whose standard score fell 1.5-*SD* below the standardized mean, all of the children in this study had PPVT standard scores between -1 and +4 *SD* of the standardized mean. While there was a significant difference in PPVT standard scores between groups, both cohorts of children had mean receptive vocabulary scores at or above average.

Localization

The ability to identify the source location of sounds on the azimuthal plane was assessed for sounds presented from different locations in the frontal hemifield under four stimulus conditions. Stimuli were either broadband, low-pass filtered, high-pass filtered, or an unpredictable mixture of these stimuli. The low- and high-pass filtered stimuli were included to evaluate performance when cues to source location are predominantly low-frequency ITDs or high-frequency ILDs, respectively.

The rationale for including a condition in which the stimulus was unpredictable was to interfere with the listener’s use of monaural spectral shape cues to source location. When the spectral shape of the stimulus is variable and unpredictable, monaural spectral shape cues associated with stimulus location are difficult to differentiate from changes in the spectral characteristics of the stimulus. By comparing listener performance across stimulus conditions, we can infer the extent to which a listener uses ITDs, ILDs, and/or monaural spectral shape cues to localize sound sources on the azimuthal plane.

Stimuli. Pink noise bursts (200-ms) gated with 20-ms raised-cosine ramps were filtered to create three separate stimuli: full-spectrum (all-pass, AP; 125–6000 Hz), low-pass (LP; 125–500 Hz), and high-pass (HP; 1500–6000 Hz). Filter roll-offs were 48-dB/octave. Stimuli were presented at 75 dB SPL with a ±5-dB level rove, to discourage participants from using overall level as a cue to location.

Procedure. This experiment was completed in a double-walled sound-treated booth (10 ft x 10 ft) using an array of 11 powered loudspeakers (JBL LSR305, Los Angeles, CA), spaced at equal intervals in a 180°-hemifield with a 2-m diameter. Participants sat in the center of the loudspeaker array, equidistant from each speaker and facing the middle speaker (0° azimuth). Chair height was adjusted individually such that the participant’s ears were approximately level with the center of the loudspeaker cones. Each loudspeaker was connected to one channel of a 24-channel soundcard through a balanced line (MOTU 24i, MOTU, Cambridge, MA). The soundcard was controlled via USB by a laptop running MATLAB (MathWorks, Natick, MA). Loudspeakers were labeled with numbers or pictures of animals, depending on the participant’s age and/or preference. A picture of Mickey Mouse was located just below the center loudspeaker at 0° azimuth; this picture was referenced to center the participant during testing. Stimuli were calibrated using a microphone suspended from the booth ceiling, at the center of the arc and level with the loudspeaker cones. Participants completed one run for each stimulus (AP, LP, HP and Mixed). Each run consisted of 33 trials, with the stimulus presented from each speaker a total of three times. Stimulus location was randomized with the restriction that the stimulus was not presented from the same speaker in sequential trials. The order of the four stimulus conditions was randomized across participants with NH. After the first child with UHL completed testing (UHLa), the remaining children with UHL always completed the AP condition first[3]. The decision to start with the AP condition was motivated by two factors: (1) some of the youngest children, regardless of hearing status, were unable to complete all four stimulus conditions due to fatigue, boredom, and task difficulty, and (2) if a child demonstrated performance at chance level in the AP condition with all stimulus cues available, they would likely perform at chance level in the remaining stimulus conditions.

During testing, the experimenter sat in a chair behind and to the right for participants with NH or to the side of the better-hearing ear for participants with UHL. The experimenter controlled stimulus presentation and scored participant responses on the laptop running MATLAB. The experimenter did not initiate a trial until the participant was facing the front loudspeaker located at 0° azimuth. The participant was instructed to indicate the source location of noise bursts by stating the number or animal associated with loudspeaker that made the noise. Participants were told that the noise could come from any of the loudspeakers, and that a recording of the word “Ready,” spoken by a male talker, would immediately precede each noise burst. Participants were instructed that the word, “Ready” would always originate from the center loudspeaker to remind them to face forward during the stimulus presentation and to

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[3] One child (UHLm) completed the Mixed condition first due to experimenter error.

indicate that a trial was about to begin. Participant head position was not restrained during trials. Head turns to locate the sound source were encouraged only after the noise burst was presented. Guessing was encouraged. Puppets were used to reinforce responses and maintain attention to the task for younger participants, as needed. If the participant was talking during stimulus presentation or was otherwise inattentive, the experimenter could repeat presentation of that stimulus. Three children with NH and one child with UHL required one stimulus repetition, and one child with UHL who completed aided and unaided testing required multiple stimulus repetitions.

This protocol took 30–60 min to complete, depending on participant age. We were unable to collect data on all conditions for one child with NH (age 5.2 years) and five children with UHL: UHLa did not complete AP, UHLb only completed AP, UHLc only completed AP and Mixed, UHLg only completed the AP and HP conditions, and UHLm did not complete the Mixed condition.

Performance metric. Absolute localization of sound sources was quantified as root-mean-square (RMS) error in degrees.

Spatial release from masking

Spatial release from masking (SRM) was assessed in the same manner as described by Corbin et al. (2017), who evaluated the effect of a simulated UHL on SRM in listeners with NH. Identical procedures were employed to facilitate a comparison of the effect of acute (simulated conductive) versus longstanding (permanent sensorineural or mixed) UHL on children's SRM. Masked SRTs were obtained in the presence of co-located or spatially separated competing speech or noise. The SRM was quantified as the difference between thresholds in the co-located and spatially separated conditions.

Stimuli. Target stimuli were Revised Bamford-Kowal-Bench (BKB) sentences (Bench et al., 1979). The BKB corpus contains 336 sentences, organized in 21 lists of 16 sentences each. Each BKB sentence contains 3–4 keywords, and there are 50 keywords in each 16-sentence list. The BKB sentences were recorded in a sound-treated room by an adult female speaker whose native language was American English. Recordings were digitized at 44.1 kHz, with a resolution of 32 bits, and saved to disk as wav files. Wav files were RMS normalized and down sampled to 24.4 kHz before presentation.

The masker was either TTS or SSN. Following Calandruccio et al. (2014), the TTS was composed of recordings of two female talkers reading different passages from the children's story *Jack and the Beanstalk* (Walker, 1999). Each talker was recorded independently. Silent pauses of $\geq$ 300 ms were manually removed from each masker stream to minimize the potential for dip listening. Masker streams were separately RMS-normalized prior to summing. The final 1.4-min masker sample ends at a word boundary for both speech streams. The long-term magnitude spectrum of the TTS and SSN were the same.

The selection and presentation of stimuli was controlled by a custom MATLAB script. Target and masker stimuli were routed through independent channels of a real-time processor (Tucker Davis Technology; RZ6), amplified (Applied Research Technology; SLA-4), and presented through a pair of loudspeakers (JBL; Professional Control 1). Target stimuli were always presented from the front of the participant (0°). The masker was presented from 0°, +90°, or -90° relative to the participant, according to the spatial condition.

Procedure. The participant was seated in the center of a 7 x 7 ft, single-walled sound-treated booth, approximately 3 ft from each of two loudspeakers. To calibrate experimental stimuli prior to testing, a microphone was suspended 2 ft above the participant's chair, approximately level with the center of the loudspeaker cones. Microphone position during calibration was intended to approximate the position of participants’ ears during testing. Chair height was not adjusted for individual participants. Calibration was completed with all equipment and furniture required for experimental testing in the booth (e.g., experimenter desk, chair, computer, and keyboard). The orientation of the participant’s chair depended on the spatial condition; participants faced the right speaker for the 0° and -90° conditions, and the left speaker for the +90° conditions.

Participants completed a total of six listening conditions: two maskers (TTS and SSN) at three spatial locations (0°, +90°, and -90° azimuth). Testing began with a randomly selected masker location. All masker conditions (TTS or SSN) for that location were completed in random order before proceeding to the next masker location. For each age- and sex-matched pair of children, the SRTs for the three spatial locations are labeled relative to the side of the affected ear of the child with UHL. The UHL comparison ear was randomly selected for adults with NH, with the proportion of left and right ears matching the distribution of left and right UHL in the group of children with UHL. Accordingly, the SRTs are referred to as $\mathrm{SRT}_{\mathrm{Co\text{-}loc}}$ (target and masker co-located), $\mathrm{SRT}_{\mathrm{Ipsi\text{-}UHL}}$ (masker ipsilateral to the UHL), and $\mathrm{SRT}_{\mathrm{Contra\text{-}UHL}}$ (masker contralateral to the UHL). The listening conditions are the same as those illustrated in Figure 1.

During testing, the experimenter was seated behind the participant at a desk with a computer monitor and keyboard. The experimenter controlled the MATLAB program and scored the participant’s verbal responses on this computer. The experimenter did not initiate a trial until the participant was facing the correct loudspeaker. Participants were told that they would initially hear two females talking or a noise that sounded like wind from the front or side loudspeaker, and then a female would say a sentence from the front loudspeaker. They were instructed to ignore the competing speech or noise, and to repeat the sentences spoken by the female from the front loudspeaker. Guessing was encouraged, and participants were told to repeat back any words they may have heard, since scoring was completed on a word-by-word basis. The experimenter scored each keyword as “correct” only if the entire word was repeated accurately, including pluralization and tense. If the participant did not respond within 5 s after the end of a given target sentence, the experimenter marked all keywords for that sentence as “incorrect.” Participants were not provided with formal feedback, but verbal encouragement was provided, particularly for the youngest children (e.g., “Keep it up!”, smiles, head nods, and sticker charts). The experimenter reinstructed participants during testing if they did not maintain head orientation to the appropriate loudspeaker.

Performance metric. SRTs were defined as the average signal-to-noise ratio (SNR) required for 50% correct keyword identification determined by a 1-up, 1-down adaptive tracking procedure (Levitt, 1971). The sum of the target and masker level was fixed throughout trials at 75 dB SPL. The first adaptive track for each masker and spatial condition was initiated at an SNR that was 10 dB above the expected SRT based on pilot data. For children with NH, this level was 15 dB SNR for co-located and 10 dB SNR for spatially separated conditions. For children with UHL, this level was 15 dB SNR for both co-located and spatially separated conditions. For adults with NH, this level was 10 dB SNR for co-located and 5 dB SNR for spatially separated conditions. Subsequent adaptive tracks began at an SNR that was 10 dB above the previous SRT for the associated masker and spatial condition. For the purpose of the adaptive track, a sentence was considered to be “correct” if more than half of the keywords were repeated accurately, and “incorrect” if fewer than half of the keywords were repeated accurately. If exactly half of the keywords were accurately repeated, a random number was generated to determine whether the sentence would be considered as “correct” or “incorrect” with respect to the adaptive procedure. When a sentence was “incorrect,” the SNR was increased (improved) by increasing the target level and decreasing the masker level after. When a sentence was “correct,” the SNR was decreased (worsened) by reducing the target level and increasing the masker level. The initial step size was 4 dB. Following the first two reversals, step size decreased to 2 dB. A trial was terminated after eight reversals. The SNRs at the final six reversals were averaged to compute the SRT.

A random number generator was used to select the initial target sentence presented to each participant. Sentences were then presented sequentially so that the participant did not hear the same sentence twice within a test session. Each SRT estimation track required 16–20 sentences. For example, if the randomly selected initial target sentence was sentence 12 of list 5, the first SRT estimation track would proceed sequentially through the remainder of list 5 (sentences 13–16) and then move on to list 6, continuing until an SRT was obtained. If the first SRT track ended with sentence 14 of list 6, the next SRT estimation track would begin at sentence 15 of list 6. This general succession of sentence presentations was followed through the entire experiment. Data collection in each masker and spatial condition continued until two SRTs within 3 dB of each other were obtained, with the caveat that no more than four SRTs could be obtained in a given masker-spatial condition. To meet this criterion, 9/15 children with NH, 8/15 adults with NH, and 13/15 children with UHL required 3 SRTs in at least one masker-spatial condition. For each masker-spatial condition, the two estimates of SRT that were within 3 dB of each other were averaged to represent the final SRT, which was used in subsequent analyses. Therefore, 6 average SRTs were calculated for each participant. A minimum of 192 sentences (12 SRTs estimated using 16 sentences each) and a maximum 300 sentences (15 SRTs estimated using 20 sentences each) were presented to obtain the 6 average SRTs for each masker-spatial condition. This protocol was typically completed within 1 hr for adults and 1.25–2 hrs for children, depending on the number of breaks taken. Children who completed the protocol aided and unaided did so on different days, weeks apart. For those participants, repetition of sentences across sessions was unavoidable given that a minimum of 384 sentences were required to obtain a total of 12 average SRTs (6 aided, 6 unaided) and the BKB corpus contains a total of 336 unique sentences.

The SRM was quantified as the difference between SRTs obtained when the target and masker were co-located and SRTs obtained when the masker was spatially separated at +90° or -90° from the midline, referenced to the side of the children's UHL. This is represented as follows:

$$\mathrm{SRM}_{\text{Ipsi-UHL}} = \mathrm{SRT}_{\text{Co-loc}} - \mathrm{SRT}_{\text{Ipsi-UHL}}$$

$$\mathrm{SRM}_{\text{Contra-UHL}} = \mathrm{SRT}_{\text{Co-loc}} - \mathrm{SRT}_{\text{Contra-UHL}}$$

Subjective outcome measures

The relationship between the functional listening abilities of children with UHL and SRM was evaluated using two of the four subscales of the APHAP and all three subscales of the SSQP. Parents were instructed to complete both the APHAP and SSQP according to their child's typical listening condition. For UHLd, UHLf, UHLm, and UHLp, the typical listening condition was aided[4]. For those children, analyses will compare scores on the APHAP and SSQP with SRM in the typical listening condition (i.e., with their personal hearing aid or CROS system).

APHAP. Parents of children with UHL completed the Background Noise and Ease of Communication subscales of the APHAP, which is a modified version of the Abridged Profile of

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[4] The typical listening condition noted by the parent of UHL14 on the APHAP was unaided. UHL14 reportedly used a CROS system exclusively (and inconsistently) at school

Hearing Aid Performance (Cox & Alexander, 1995). The APHAP consists of 24 items, or statements, about children's communication skills or perception of sounds in everyday listening situations. The 24 items are divided into four six-item subscales: Aversiveness, Background Noise (BN), Ease of Communication (EC), and Reverberation. The score obtained from the EC subscale reflects the effort a child expends to communicate under relatively easy listening conditions, while the score calculated on the BN subscale provides insight regarding a child's speech understanding in the presence of multiple talkers or other competing noise. The total score for each APHAP subscale represents the average proportion of perceived problems (1% [never] to 100% [always]) that children experience in the EC and BN domains in everyday situations. The questionnaire takes 10 min or less to complete.

SSQP. The Speech, Spatial, Qualities hearing scale (SSQ; (Gatehouse & Noble, 2004) was designed to assess the listening abilities of adults who are hard of hearing across a range of real-world environments in which performance relies heavily on binaural hearing. The parent version of the SSQ (SSQP; Galvin & Noble, 2013) was used for this study. The SSQP contains three subscales, each comprised of questions regarding a child's listening abilities in a variety of situations. For each listening situation queried, parents rate their children's performance on a scale of 0 (minimal ability) to 100 (maximal ability). The Speech subscale contains eight questions to query a child's ability to follow conversations in different listening scenarios. The Spatial subscale includes five questions that assess a child's ability to locate talkers in the presence of background noise. The Qualities of Hearing subscale comprises eight questions that probe the child's awareness of -- as well as their ability to identify and selectively attend to -- sounds in their environment. The SSQP was completed according to the instructions outlined by Galvin and Noble (2013).

Performance metric. Given that scores on the BN and EC subscales of the APHAP are highly correlated (Hillock-Dunn et al., 2015), a composite score was obtained for each child by averaging the scores on these subscales. A higher composite score indicates greater difficulties in common listening situations. In contrast, a higher score on a subscale of the SSQP reflects better abilities in the associated listening scenarios.

Statistical analyses

Statistical analyses were conducted in SPSS (Version 25, IBM Corporation, 2017) and in R Version 3.5.0 (R Core Team, 2018) using the following packages: car (Fox & Weisberg, 2011), fields (Nychka, Furrer, Paige, & Sain, 2017), nlme (Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 2018), and reshape2 (Wickham, 2007). In the subsequent figures and analyses, age was represented on a logarithmic scale to account for the observation that psychophysical performance improves rapidly among younger participants and more gradually with increasing age. Degree of UHL is represented as audibility at 75 dB SPL using the SII. The rationale behind quantifying hearing impairment this way was that the SII would better capture the amount of the average speech spectrum available to each participant with UHL than pure-tone average. This was important given the focus of the present study on quantifying the functional communication deficits experienced by children with UHL, particularly with respect to masked speech recognition.

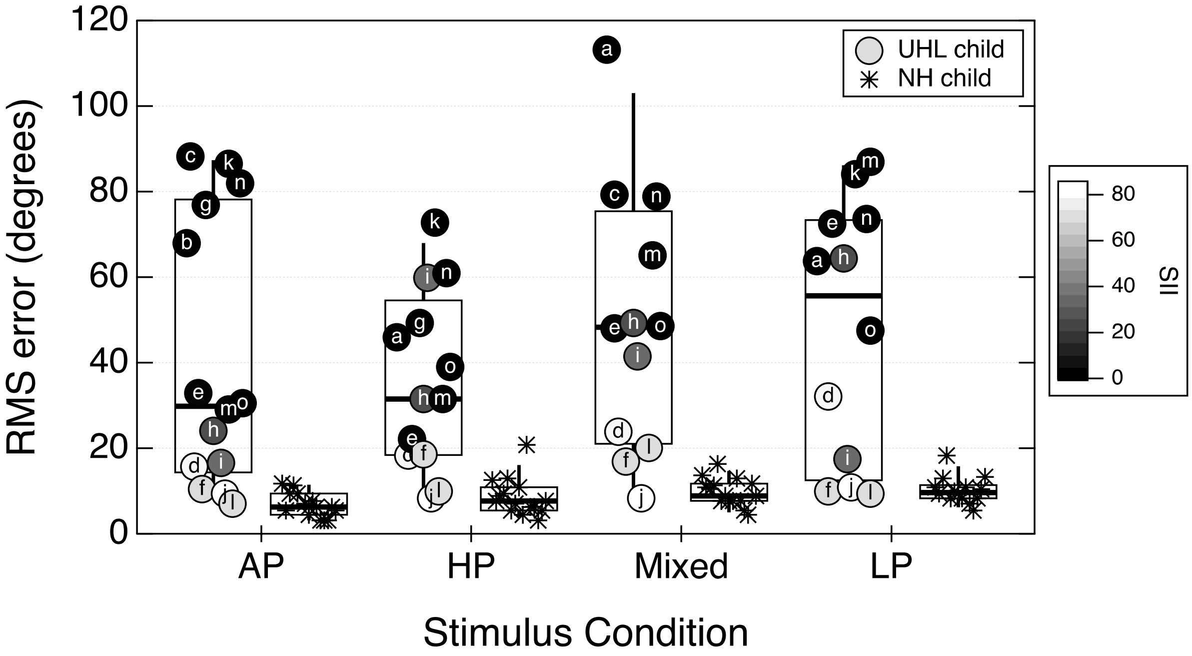
Results

Localization

Localization performance is quantified as RMS error, with larger values representing poorer performance. Figure 4 illustrates the distribution of RMS error in degrees for children with and without UHL, in the absence of any personal hearing devices. Results in the four stimulus conditions are arranged from left to right in order of increasing median values for RMS error in children with UHL: All-Pass (AP), High-Pass (HP), Mixed, and Low-Pass (LP). Each box represents the interquartile range (25th–75th percentile) of RMS values for each group of participants. The vertical lines extending from each box encompass the 10th and 90th percentiles, while the horizontal line within each box represents the median RMS value. Values of RMS error for individual children with UHL (circles) and children with NH (stars) overlay each boxplot. The shading of the individual data points for children with UHL corresponds to the unaided SII value calculated for their poorer-hearing ear, and the letter corresponds to the participant ID indicated in Table 4. An SII value of 0 indicates 0% audibility at 75 dB SPL, while an SII of 84 indicates 84% audibility.

Figure 4. Distribution of root-mean-square (RMS) error in degrees as a function of stimulus condition for children with unilateral hearing loss (UHL) and children with normal hearing (NH).

Each box represents the interquartile range (25th–75th percentile) of RMS values for each group of participants, and vertical bars indicate the 10th and 90th percentiles. Shading of individual data points for children with UHL corresponds to audibility in the affected ear represented by the Speech Intelligibility Index (SII) value calculated for a 75 dB SPL standard speech passage. Participant ID is indicated with letters (see table 4).



A few trends are evident from the data plotted in Figure 4. First, children with UHL perform worse on average than their peers with NH in all stimulus conditions. The median RMS error in the AP, HP, Mixed and LP conditions was 29.8°, 31.5°, 48.3°, and 55.6° for children with UHL, and 6.3°, 7.7°, 8.9°, and 9.7° for children with NH, respectively. Second, the performance of children with UHL was substantially more variable than that of children with NH in all stimulus conditions. The standard deviation (*SD*) of RMS error across participants ranged from 20.7° to 31.5° for children with UHL, and from 2.8° to 4.4° for NH controls. Third, there seems to be an effect of unaided SII on the performance of children with UHL. Recall from Table 4 that only six of the fifteen children with UHL had an unaided SII greater than five in the impaired ear. Those children tended to perform better on the localization task than their counterparts with more severe UHL in all four conditions, in some cases performing similarly to the NH group. At least one child with UHL had an RMS error within ± 2 *SD* of the mean RMS error for NH children in all four stimulus conditions, including AP (n = 3), HP (n = 2), Mixed (n = 1), and LP (n = 3).

Evaluating just the data of children with UHL, a repeated-measures analysis of variance (rmANOVA) with Greenhouse-Geisser correction indicates a non-significant trend for an effect of stimulus condition ($F(1.5, 13.9) = 3.48$, $p = 0.069$). Variability in the severity of loss across children with UHL could have affected our ability to observe differences across conditions. In a second rmANOVA, including just the children with UHL who have unaided SII values of <5, there is a significant main effect of stimulus condition ($F(3, 9) = 4.70$, $p = 0.031$). One-tailed paired contrasts indicate no difference in performance between AP and HP conditions (p = 0.245), a non-significant trend for a difference between AP and Mixed conditions ($p = 0.066$); there were significant differences between HP and Mixed ($p = 0.013$), and between HP and LP (p

= 0.041) conditions. This is broadly consistent with the prior expectation that children whose UHL precludes access to binaural difference cues may be able to localize sound based on the monaural spectral shape cues that are present in the AP and HP conditions. Poorer performance in the LP and Mixed conditions would be predicted based on the absence reliable spectral cues in these conditions.

No consistent benefit of personal hearing device was observed among the children who returned to complete aided testing. Across all conditions tested, localization performance tended to be worse with than without personal hearing devices, evidenced by an increase RMS error of 0.5°–31.5°.

Comparing the performance between children and adults with NH, a rmANOVA indicates a significant main effect of age group ($F(1, 27) = 4.59$, $p = 0.041$, and stimulus condition ($F(3, 81) = 11.82$, $p < 0.001$), but no interaction ($F(3, 81) = 1.62$, $p = 0.192$). The mean RMS error was 8.6° and 6.3° for children and adults with NH. Paired contrasts indicate a significant difference in performance between the AP condition and the LP, HP, and Mixed conditions ($p < 0.005$). None of the comparisons between the LP, HP, and Mixed conditions were statistically significant ($p \geq 0.098$).

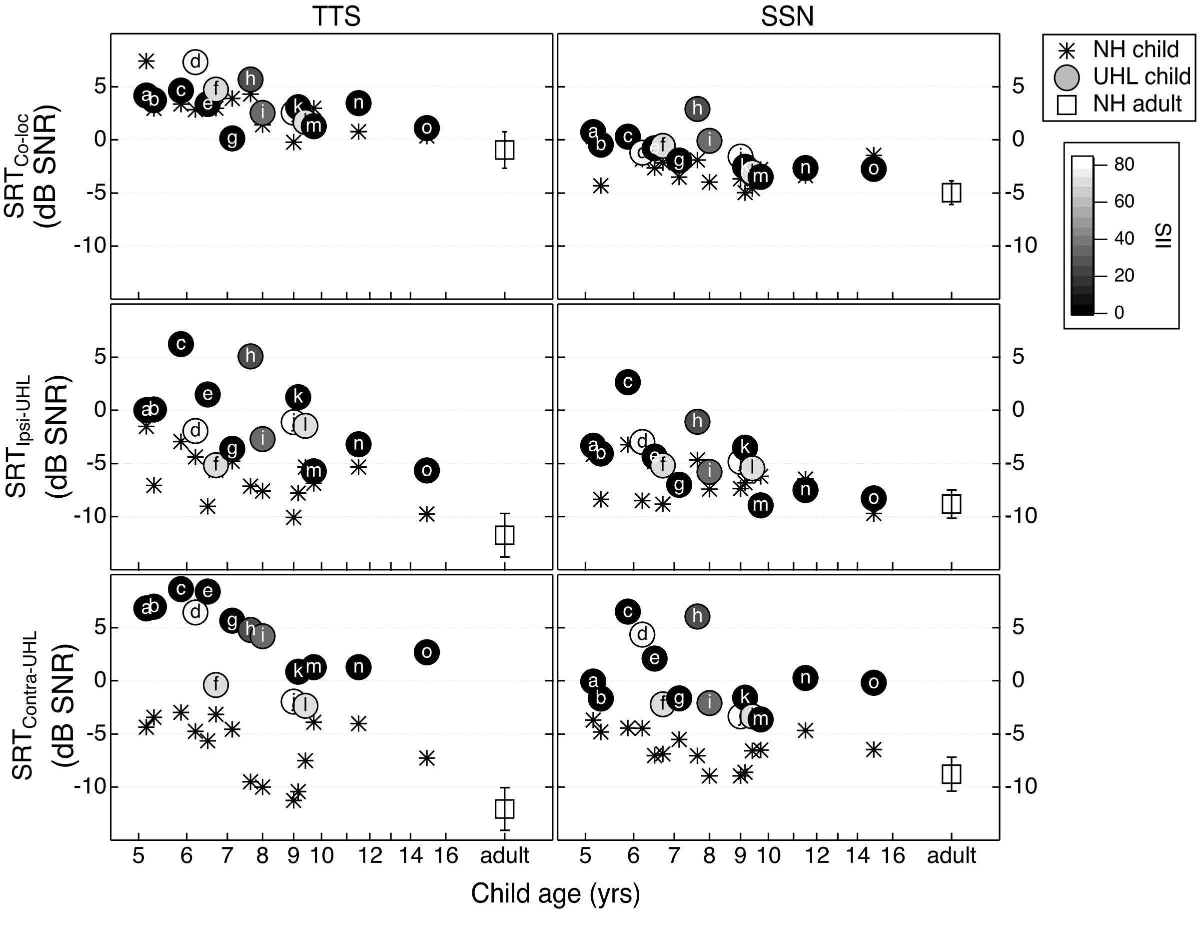
Speech perception

The effect of UHL on children's speech recognition in co-located and spatially separated maskers will be explored first. In order to account for the developmental effects of masked speech recognition observed among children with and without UHL, the results from three separate linear mixed models will be reported. Then, the effect of age on SRM in participants with NH will be described.

In Figure 5, individual child and average adult SRTs obtained without personal hearing devices are plotted as a function of age. Panels on the left show SRTs in TTS, and panels on the right show SRTs in SSN. Performance in the co-located target-masker condition ($\mathrm{SRT}_{\mathrm{Co\text{-}loc}}$) is shown in the first row of panels. The second and third rows of panels show performance when the masker is spatially separated to the side ipsilateral or contralateral to the UHL ($\mathrm{SRT}_{\mathrm{Ipsi\text{-}UHL}}$ and $\mathrm{SRT}_{\mathrm{Contra\text{-}UHL}}$), respectively. Lower values of SRT indicate better performance. Following the plotting conventions of Figure 4, children with UHL are represented by circles and age-matched children with NH are represented by stars. The shading of the individual data points for children with UHL corresponds to the unaided SII value calculated for their poorer-hearing ear, while the lettering indicates the participant ID noted in Table 4. The average adult SRT (± 1 *SD*) is depicted by the square at the far right of each panel, to provide a reference for mature performance

Figure 5. Speech recognition thresholds (SRTs) as a function of child age.

SRTs correspond to the signal-to-noise ratio (SNR, in dB) associated with 50%-correct sentence recognition in two two-talker speech (TTS; left column) or speech-shaped noise (SSN; right column) for three different masker conditions: co-located with target speech ($\text{SRT}_{\text{Co-loc}}$), ipsilateral to the unilateral hearing loss (UHL; $\text{SRT}_{\text{Ipsi-UHL}}$), or contralateral to the UHL ($\text{SRT}_{\text{Contra-UHL}}$). Mean performance for adults is shown at the far right of each panel. Error bars for adult data points represent ±1 standard deviation (*SD*) around the mean. The same plotting conventions from Figure 4 are followed to represent the individual data points for children.



As depicted in Figure 5, there is a trend for improvement in performance with increasing age for both groups of children. The first linear mixed model examined the effect of age on children's SRTs. This linear mixed model included age as a covariate and fixed effects of masker type (TTS, SSN), masker location (co-located, ipsilateral to the UHL, contralateral to the UHL), and hearing status (UHL, NH), as well as interactions between these factors; the dependent variable was SRT. A random intercept was included for each participant to accommodate repeated measures. The results from this linear mixed model are shown in Table 5. There was a significant main effect of age ($p < 0.001$), consistent with the observation that performance was better for older children. With age accounted for as a covariate, there was a significant three-way interaction between masker type, masker location, and hearing status ($p < 0.001$). This three-way interaction indicates that the effects of masker type and masker location differ for children with and without UHL. These effects are difficult to see in Figure 5 due to the distribution of data across child age, but they are easier to see in mean data.

Table 5. Results from a linear mixed model analyzing children's speech recognition thresholds (SRTs) as a function of age.

The reference conditions for comparisons involving masker type, masker location, and hearing status are speech-shaped noise (SSN), co-located (Co-loc), and normal hearing (NH), respectively.

	Value	**Standard Error**	***df***	***t*-value**	***p*-value**
Intercept	5.80	2.15	140	2.69	0.008
Age	-4.19	1.02	27	-4.11	<0.001
TTS	5.46	0.64	140	8.57	<0.001
Ipsi-UHL	-3.89	0.64	140	-6.11	<0.001
Contra-UHL	-3.59	0.64	140	-5.62	<0.001
UHL	1.66	0.82	27	2.03	0.053
TTS x Ipsi-UHL	-5.20	0.90	140	-5.76	<0.001
TTS x Contra-UHL	-5.34	0.90	140	-5.92	<0.001
TTS x UHL	-1.02	0.90	140	-1.13	0.261
Ipsi-UHL x UHL	0.39	0.90	140	0.44	0.663
Contra-UHL x UHL	4.69	0.90	140	5.20	<0.001
TTS x Ipsi-UHL x UHL	4.30	1.28	140	3.37	0.001
TTS x Contra-UHL x UHL	4.49	1.28	140	3.52	<0.001

TTS = two-talker speech

Ipsi-UHL = masker ipsilateral to the UHL

Contra-UHL = masker contralateral to the UHL

UHL = unilateral hearing loss

Figure 6 shows group average unaided SRTs (top panel) and SRM (bottom panel). Plotting conventions follow those of Figure 5, with the group average SRT and SRM of children with UHL represented by solid circles. Similar to Figure 5, data collected in TTS and SSN are arranged in the left and right columns, respectively. Masker location relative to UHL laterality, or the ear selected for comparison in participants with NH, is indicated along the x-axis of each panel. In the bottom panels showing SRM, symbols located above the dashed line at 0 dB SRM on the y-axis indicate an average benefit of spatial separation of target and masker stimuli on the azimuthal plane for speech perception. Symbols falling below the dashed line are consistent with poorer performance when the target and masker were separated compared to when they were co-located on the azimuthal plane. The data depicted in Figure 6, along with the associated standard deviations, are also provided in Table 6.

Figure 6. Group average speech recognition thresholds (SRTs) and spatial release from masking (SRM).

Group average values for speech recognition thresholds (SRTs) and spatial release from masking (SRM) are shown as a function of masker location. Data obtained in two-talker speech (TTS) are shown in the left column, and data obtained in speech-shaped noise (SSN) are shown in the right column. Error bars represent ± 1 standard deviation (*SD*) around the group mean. Masker location is indicated as follows: Co-loc = co-located with the target, Ipsi UHL = ipsilateral to the unilateral hearing loss (UHL), and Contra UHL = contralateral to the UHL.

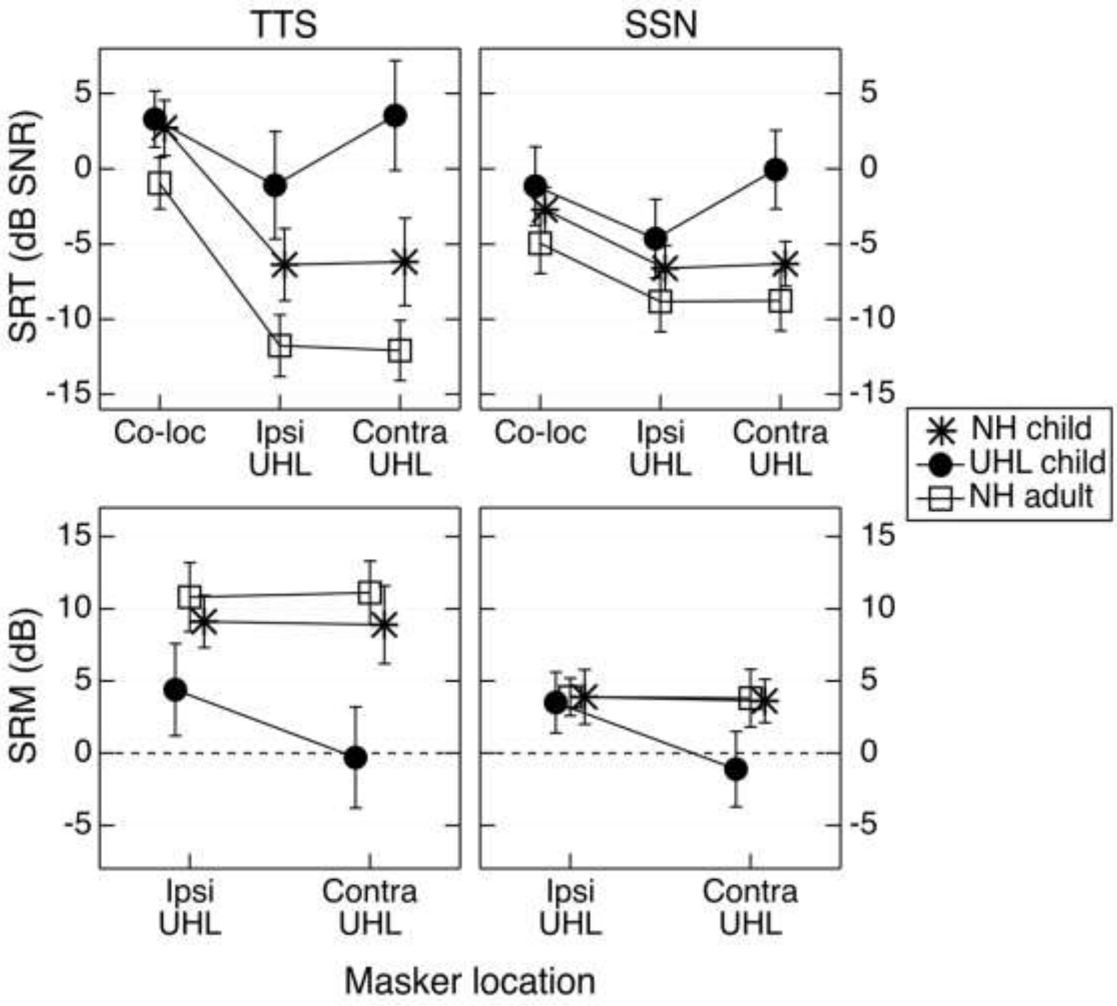


Table 6. Group average speech recognition thresholds (SRTs) and spatial release from masking (SRM).

Speech recognition thresholds (SRTs) are represented in dB signal-to-noise ratio (dB SNR). Spatial release from masking (SRM) is represented in dB. Values are reported as means and standard deviations (in parentheses).

	SRT			SRM	
	Co-loc	**Ipsi-UHL**	**Contra-UHL**	**Ipsi-UHL**	**Contra-UHL**
Two-talker speech masker					
NH children	2.7(1.9)	-6.4(2.4)	-6.2(2.9)	9.1(1.8)	8.9(2.7)
UHL children	3.3(1.9)	-1.1(3.6)	3.6(3.6)	4.4(3.2)	-0.3(3.5)
NH adults	-1.0(1.7)	-11.8(2.1)	-12.1(2.0)	10.8(2.4)	11.1(2.2)
Speech-shaped noise masker					
NH children	-2.7(1.6)	-6.6(1.8)	-6.3(1.7)	3.9(1.9)	3.6(15)
UHL children	-1.1(1.7)	-4.7(2.9)	0.0(3.3)	3.6(2.1)	-1.1(2.6)
NH adults	-5.0(1.1)	-8.8(1.3)	-8.8(1.6)	3.9(1.3)	3.8(2.0)

UHL = unilateral hearing loss

Co-loc = masker co-located with the target at 0° azimuth

Ipsi-UHL = masker ipsilateral to the UHL

Contra-UHL = masker contralateral to the UHL

Two additional linear mixed models were constructed to evaluate the effects of masker and spatial condition for children with and without UHL. In each case, there was a random intercept term for each participant, the covariate of age on a logarithmic scale, and fixed effects of masker type (TTS, SSN) and masker location (co-located, ipsilateral to the UHL, contralateral to the UHL). Results from these analyses are provided in Table 7. Focusing first on children with NH, there were significant interactions between masker type and masker location. This is indicated in Table 7 by the significant TTS x Ipsi-UHL and TTS x Contra-UHL interaction coefficients ($p<0.001$ for both). As evident in the top row of Figure 6, the average SRT for children with NH differed according to masker type by 5.4 dB in the co-located condition but only 0.1–0.2 dB in the spatially separated conditions. The benefit of spatially separating the masker to either side for children with NH was larger in the TTS (9 dB) than the SSN (3.8 dB). This is illustrated by the larger value of SRM in bottom left relative to right panels in Figure 6.

Table 7. Results from two separate linear mixed models analyzing children's speech recognition thresholds (SRTs) as a function of hearing status.

The reference conditions for comparisons involving masker type and masker location are speech-shaped noise (SSN) and co-located (Co-loc), respectively.

Children with NH	**Value**	**Standard Error**	***df***	***t*-value**	***p*-value**
Intercept	3.98	2.32	70	1.72	0.091
Age	-3.29	1.11	13	-2.96	0.011
TTS	5.46	0.56	70	9.79	<0.001
Ipsi-UHL	-3.89	0.56	70	-6.98	<0.001
Contra-UHL	-3.59	0.56	70	-6.43	<0.001
TTS x Ipsi-UHL	-5.20	0.79	70	-6.59	<0.001
TTS x Contra-UHL	-5.34	0.79	70	-6.77	<0.001

Children with UHL	**Value**	**Standard Error**	***df***	***t*-value**	***p*-value**
Intercept	9.38	3.53	70	2.66	0.010
Age	-5.12	1.69	13	-3.04	0.010
TTS	4.45	0.71	70	6.25	<0.001
Ipsi-UHL	-3.50	0.71	70	-4.92	<0.001
Contra-UHL	1.11	0.71	70	1.56	0.124
TTS x Ipsi-UHL	-0.90	1.01	70	-0.89	0.376
TTS x Contra-UHL	-0.85	1.01	70	-0.84	0.402

NH = normal hearing

UHL = unilateral hearing loss

TTS = two-talker speech

Ipsi-UHL = masker ipsilateral to the UHL

Contra-UHL = masker contralateral to the UHL

For children with UHL, there were significant main effects of masker type and masker location (TTS, $p < 0.001$; Ipsi-UHL, $p < 0.001$), but no significant interactions between the two. As seen in the top panels of Figure 6, speech recognition for children with UHL was generally poorer in TTS when compared with SSN, but the pattern of SRTs obtained across the spatial conditions was similar in both maskers. Specifically, SRTs were 3–4.5 dB better (lower) when the masker was ipsilateral to the UHL than when the masker was co-located with the target speech ($p < 0.001$). There was no difference between SRTs obtained in the co-located and Contra-UHL conditions for children with UHL ($p = 0.124$).

There was not a consistent effect of amplification in either masker. For example, the aided $\text{SRT}_{\text{Ipsi-UHL}}$ in TTS was worse for UHLd but better for UHLf and UHLm relative to unaided performance (by 2 and 3 dB, respectively). Across all locations of TTS, UHLf derived a benefit of 1 to 2.4 dB in the aided condition. Interestingly, the detriment of listening with the CROS system for UHLp was 1.5-dB less in TTS (3.8 dB) than SSN (7.0 dB) for $\text{SRT}_{\text{Ipsi-UHL}}$. There was essentially no benefit of CROS for $\text{SRT}_{\text{Contra-UHL}}$ in either masker, and only 1.7-dB benefit in TTS for $\text{SRT}_{\text{Co-loc}}$.

A metric that clearly captures the pattern of unaided SRTs across masker location noted above is SRM. As seen in the bottom row of Figure 6, children with UHL achieved substantially less SRM than children with NH for both the ipsilateral and contralateral masker in the TTS. In contrast, the difference in SRM between children with UHL and children with NH for the SSN was evident only when the masker was presented contralateral to the UHL. The average group difference in $\text{SRM}_{\text{Ipsi-UHL}}$ between children with UHL and children with NH was 4.7 dB in TTS and essentially 0 dB in SSN. In contrast, children with UHL are at a disadvantage when the masker is located on the side contralateral to their UHL (i.e., on the side of their good ear), regardless of masker type. The average group difference in $\text{SRM}_{\text{Contra-UHL}}$ was 9.2 dB in the TTS and 4.7 dB in the SSN. There does, however, appear to be an effect of UHL degree on $\text{SRM}_{\text{Contra-UHL}}$. Specifically, three of the five children who achieved $\text{SRM}_{\text{Contra-UHL}}$ values >2 dB in TTS had unaided SII values ≥ 40 (UHLf, UHLj, and UHLm). There was a less obvious effect of UHL degree on $\text{SRM}_{\text{Contra-UHL}}$ in SSN, as only one child (UHLi) achieved $\text{SRM}_{\text{Contra-UHL}}$ ≥2 dB.

Among the three children who used a hearing aid, there was no consistent benefit of hearing-aid use for $\text{SRM}_{\text{Ipsi-UHL}}$ or $\text{SRM}_{\text{Contra-UHL}}$. Interestingly, UHLd derived a 4.2-dB benefit from personal amplification in SSN for $\text{SRM}_{\text{Contra-UHL}}$, and UHLm derived a 4.5-dB benefit of personal amplification for in TTS $\text{SRM}_{\text{Ipsi-UHL}}$. In contrast, for the child who used a CROS system, SRM decreased by 1 to 6.8 dB in all conditions expect $\text{SRM}_{\text{Contra-UHL}}$, where SRM was 0.4-dB better in SSN.

Effect of age on NH performance. Attention now turns to the effect of development on the ability to benefit from target-masker separation for speech recognition in TTS or SSN for participants with NH. Recall the trend in Figure 5 for improvement in SRTs with increasing child age across the six listening conditions. This trend poses a challenge when comparing performance between children and adults. However, the effect of age is not significantly different across masker location conditions, such that there is no effect of age on SRM within the child group. This can be demonstrated using a linear mixed model with a random intercept term for each child with NH and fixed effects of age, masker type (TTS, SSN), and masker location (co-located, ipsilateral to the UHL, contralateral to the UHL); there are no interactions between age and masker type, or between age and masker location (analysis not shown). SRM was therefore selected as a metric to compare across the two groups of NH participants (children and adults).

Values of SRM were compared across age groups using a linear mixed model, with a random intercept term for each participant with NH and fixed effects of masker type (TTS or SSN) and age group (child or adult). The value of SRM used in this model was the average of $SRM_{Ipsi\text{-}UHL}$ and $SRM_{Contra\text{-}UHL}$, calculated for each participant with NH. The rationale for using mean SRM was that there is no reason to expect SRM values for participants with NH to differ based on the side of the masker presentation. As seen in Table 8, there was a significant effect of masker type ($p < 0.001$), a significant interaction between age group and masker type ($p = 0.038$) and non-significant effect of age group ($p = 0.880$). This pattern of results is illustrated in Figure 7.

Table 8. Results from a linear mixed model analyzing spatial release from masking (SRM) as a function of age in participants with normal hearing (NH).

Spatial release from masking (SRM) is represented in dB. The reference condition for comparisons involving masker type is speech-shaped noise (SSN) and for age group is adults.

	Value	**Standard Error**	***df***	***t*-value**	***p*-value**
Intercept	3.84	0.44	28	8.63	<0.001
Age Group	-0.10	0.63	28	-0.15	0.880
TTS	7.12	0.60	28	11.80	<0.001
Age group x TTS	-1.86	0.85	28	-2.17	0.038

TTS = two-talker speech

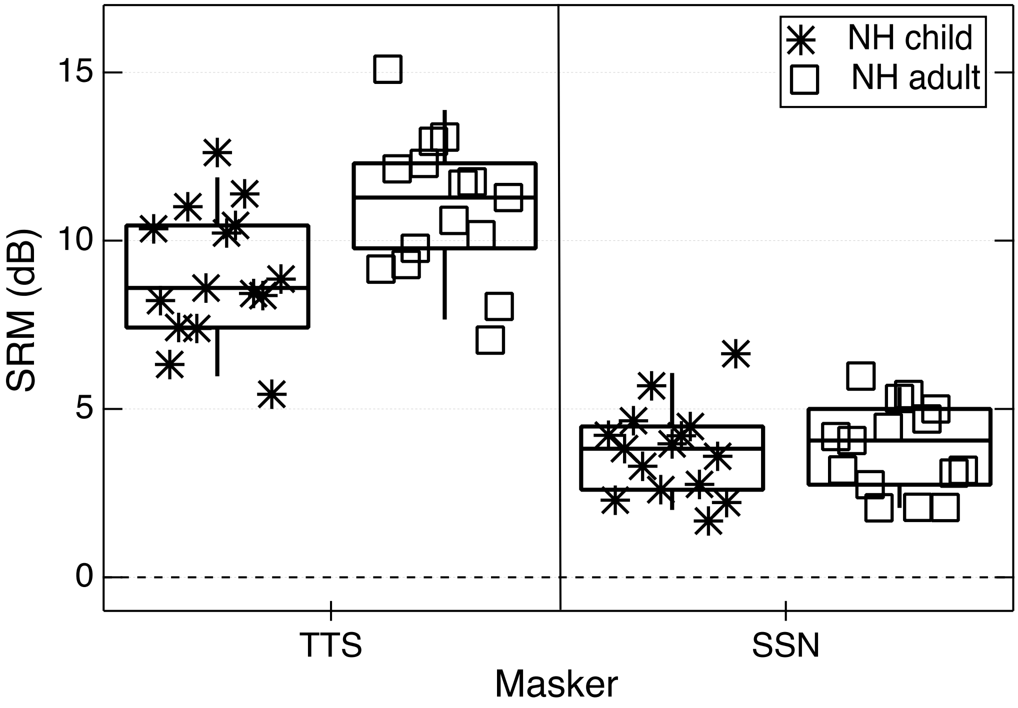
Figure 7 displays the distribution of SRM in TTS and SSN for children and adults with NH. Each box represents the interquartile range (25th–75th percentile) of SRM values for each group of participants and masker type. The vertical lines encompass the 10th and 90th percentiles, while the horizontal line within each box represents the median SRM. Individual SRM values for children (stars) and adults (squares) overlay each boxplot. Both children and adults with NH experience greater SRM for TTS than SSN. In SSN, the SRM for children with NH is virtually indistinguishable from that of adults with NH (adult *M* = 3.8, *SD* = 1.3; child *M* = 3.7, *SD* = 1.3). However, in the TTS, adults achieved 2-dB larger values of SRM on average than children (adult *M* = 11.0, *SD* = 2.1; child *M* = 9.0, *SD* = 2.0).

Figure 7. Spatial release from masking (SRM) for children and adults with normal hearing (NH).

Distribution of spatial release from masking (SRM, dB) is shown for children and adults with normal hearing (NH) as a function of masker type.

TTS = two-talker speech

SSN = speech-shaped noise



APHAP and SSQP

For children with UHL, the relationship between SRM and parents' subjective ratings of their children's everyday functional listening abilities was assessed. Recall that parents were instructed to complete the APHAP and SSQP for their child's typical listening condition. For UHLd, UHLf, UHLm, and UHLp the typical listening condition was aided. Subsequently, aided rather than unaided performance on the SRM task for UHLd, UHLf, UHLm, and UHLp was included in the analyses described below. Results for the APHAP will be discussed first. Figure 8 shows the relationship between SRM for children with UHL as a function of their scores on the APHAP. As in previous figures, symbol shading indicates the SII at 75 dB SPL in the ear with UHL and lettering corresponds with participant ID from Table 4. Each column represents the masker type, with data obtained in TTS and SSN maskers arranged in the left and right columns, respectively. The top row shows SRM for the masker ipsilateral to the UHL, and the bottom row shows SRM for the masker contralateral to the UHL. On the x-axes, higher scores on the APHAP correspond with greater problems experienced in everyday listening environments. Interestingly, there was no evidence that parents of children with greater audibility (higher SII) in the ear with UHL rated their children as experiencing fewer problems on the APHAP ($r_s = -0.28$, $p = 0.155$, one-tailed).

At the outset we predicted that deficits in SRM associated with UHL would be reflected in parents' reports of their children's listening difficulties. Given that the largest group effects were seen when the masker was contralateral to the ear with UHL, an association between APAHP scores and values of SRM should be most evident in these conditions. There was a significant correlation between APHAP scores and the $\mathrm{SRM}_{\mathrm{Contra\text{-}UHL}}$ for the TTS ($r = -0.50$, $p = 0.032$, one-tailed). The correlation between APHAP scores and $\mathrm{SRM}_{\mathrm{Contra\text{-}UHL}}$ for SSN approached significance (*r* = -0.38, *p* = 0.08, one-tailed). The correlations between APHAP scores and the $\mathrm{SRM}_{\mathrm{Ipsi\text{-}UHL}}$ did not approach significance for either masker ($p \geq 0.22$). While we did not make any predictions regarding a relationship between APHAP scores and RMS localization error, we decided to assess the extent to which ratings on the APHAP reflect spatial hearing on this task. The correlation between APHAP scores RMS localization error tended to be positive (*r* = 0.25-0.45), as expected if greater perceived difficulty was associated with larger error, but this association only approached significance in the AP condition (*r* = 0.45, p = 0.054, one-tailed). Taken together, these results suggest an association between APHAP scores and spatial hearing abilities. Although the association between APHAP scores and degree of hearing loss is not strong, it is possible that degree of UHL could play a role.

Figure 8. Spatial release from masking (SRM) as a function of composite scores on the Parent's Version of the Abbreviated Profile of Hearing Aid Performance (APHAP).

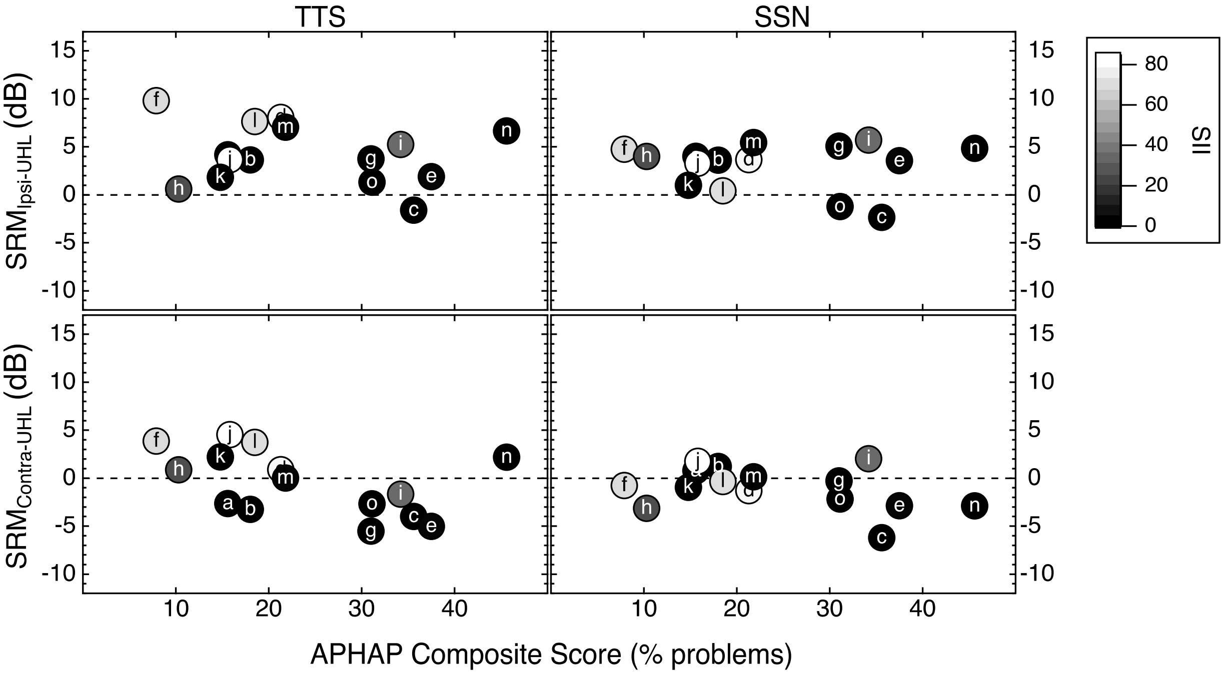
Spatial release from masking (SRM) as a function of composite scores on the Parent's Version of the Abbreviated Profile of Hearing Aid Performance (APHAP) for children with unilateral hearing loss (UHL). Symbol shading corresponds to Speech Intelligibility Index (SII) values at 75 dB SPL in ear with UHL. Participant ID is indicated by symbol lettering.

$SRM_{Ipsi\text{-}UHL}$ = spatial release from masking when the masker is ipsilateral to the UHL

$SRM_{Contra\text{-}UHL}$ = spatial release from masking when the masker is contralateral to the UHL

TTS= two-talker speech

SSN = speech-shaped noise



Recall that parents were asked to complete the SSQP at home before or after their children's visit to the laboratory. The rationale for doing this was to accommodate the implementation of an observation period prior to completion of each subscale, in accordance with the test manual. Not all parents completed these questionnaires, however: only 12 SSQP Speech subscales and 9 each of the SSQP Spatial and Qualities subscales were returned. Statistical analyses were therefore not performed on the SSQP data. However, there did not appear to be a relationship between SRM and scores on any of the SSQP subscales for either masker.

Discussion

The overall goal of the present study was to investigate the spatial hearing abilities of children with permanent sensorineural or mixed UHL on a combination of psychoacoustic and subjective outcome measures that are reliant on binaural hearing. This goal was accomplished by assessing the performance of children with UHL on the following three measures: (1) sound source localization on the azimuthal plane in AP, LP, HP, and Mixed stimulus conditions, (2) SRM in TTS and SSN, and (3) parental ratings of functional auditory performance on the APHAP and SSQP. As expected based on published data, UHL was associated with poorer localization on the azimuthal plane and poorer masked speech recognition, particularly when a TTS masker was contralateral to the UHL. These detrimental effects of UHL were associated with children's functional listening abilities as assessed by parent report on the APHAP. These findings are discussed in detail below.

Effects of UHL on sound source localization

Children with UHL exhibited poorer performance and larger individual differences than their peers with NH across all listening conditions. This general finding is consistent with data from previous studies of sound source localization abilities among this population. For instance, Reeder et al. (2015) assessed the localization abilities of children with severe-to-profound sensorineural UHL and age-matched peers with NH using a monosyllabic word preceded by the carrier “Ready.” Based on the boxplots reported in that study, the median RMS error of children with UHL and children with NH are estimated to be 26° and 5°, respectively; these errors can be compared with 29.8° and 6.3° reported in the AP condition of the present study. Variability in performance among the children with UHL was notably greater in the present compared to the published study (*SD* = 31.5° versus 13.5°). Apart from differences in stimuli between the two studies, differences in the loudspeaker arrays as well as the distribution of age and UHL degree among participants could have contributed to the greater variability noted among children with UHL in the present study. The source locations were distributed from +90° to -90°azimuth in the present study, and from +70° to -70° azimuth in Reeder et al. (2015). Localization performance is known to be better near the midline (0°) than the side (Blauert, 1997). Children ranged in age from 5 to 14 years (UHL *M* = 8.2, *SD* = 2.6 years; NH *M* = 8.0, *SD* = 2.5 years) in the present study, and from 6 to 17 years (*M* = 12.0 years for both groups) in the study by Reeder et al. (2015). Given the effect of age on the performance of participants with NH in the current study, it is possible that the inclusion of younger participants contributed to the increased variability in localization performance in the present study.

Unique to this study, localization was evaluated under four stimulus conditions to indirectly assess the extent to which children with UHL use binaural difference and monaural spectral shape cues. Results from statistical analyses including only the children who had an SII of 0 in the affected ear revealed a statistically significant effect of stimulus condition on RMS error. There was not a significant difference in RMS error between AP and HP conditions. However, performance was significantly better in the HP condition than the LP condition, and there was a non-significant trend for better performance in the HP condition than the Mixed condition. The trend for poorer performance in the LP and Mixed conditions than the AP and HP conditions suggests that at least some children with severe-to-profound UHL rely on monaural spectral shape cues to localize sounds on the azimuthal plane. In the LP and Mixed conditions, spectral shape cues do not reliably indicate source location on the azimuth. For the LP condition, this is because the lack of high-frequency content in the LP stimulus precludes spectral differences between ears. In the Mixed condition, the variable and unpredictable nature of the spectral shape of the stimulus makes it difficult to differentiate monaural spectral shape cues associated with stimulus location from changes in the spectral characteristics of the stimulus. While it is theoretically possible for participants to memorize the three stimulus options (AP, HP, and LP) in the Mixed condition, thereby making spectral shape cues viable for a subset of trials, this seems unlikely. A larger number of children with mild to moderate-severe UHL are needed to determine the role of monaural spectral shape cues in that population. No evidence of an improvement in performance when listening with a HA was observed among the four children who completed testing both with and without their personal hearing devices. There was, in fact, a trend for poorer performance in the aided condition for these children.

Children with NH performed significantly more poorly on the sound source localization task compared with adults. The mean RMS error was 8.6º for children with NH and 6.3º for adults with NH. Performance for both age groups was best in the AP stimulus condition, followed by the HP, LP, and Mixed conditions. The effect of age on the performance between children and adults with NH is generally consistent with results from other studies suggesting a developmental effect of sound source localization (Grieco-Calub & Litovsky, 2010; Johnstone et al., 2010; Litovsky & Godar, 2010; Martin, Johnstone, & Hedrick, 2015; Van Deun et al., 2009).

Effects of UHL on masked speech recognition and SRM

The effect of UHL on masked SRTs in spatially coincident target and masker stimuli will be discussed first since it is the baseline condition from which SRM is derived. When the target and masker are co-located in front of a listener, there are no differences in interaural time or level between stimuli. Therefore, effects of UHL in the $\text{SRT}_{\text{Co-loc}}$ condition cannot be explained by absence of binaural difference cues. Yet there is precedent in the literature for a small (1–3 dB) detrimental effect of UHL on performance when target and masker stimuli are co-located in front of the listener. This effect is explained in terms of binaural summation. In listeners with NH, binaural summation is the benefit of receiving input from two ears, a benefit that is thought to reflect access to two representations of the target and masker stimuli at the level of the central auditory system.

In the present study, there was a small effect of UHL on $\text{SRT}_{\text{Co-loc}}$ in SSN (1.6 dB) and TTS (0.6 dB). These values are similar to those observed by Corbin et al. (2017) who investigated the effect of simulated UHL using the same stimuli and experimental task. In that study, a group of children ages 8 to 10 years completed the SRM task both with and without a simulated moderate conductive UHL. Corbin et al. (2017) observed a statistically significant summation effect in SSN (1.3 dB) but not TTS (0.7 dB). Among the studies that have assessed speech recognition for co-located target and masker stimuli at 0° azimuth in children with sensorineural UHL, the benefit of binaural hearing varies. Similar to the present study, examination of boxplots provided by Reeder et al. (2015) suggests a difference of 0.3 dB between SRTs in competing speech for their sample of 20 children with severe-to-profound UHL compared to NH controls. Griffin et al. (2018) reported a larger benefit of binaural hearing for sentence recognition in competing speech (1.8 dB) than competing noise (0.8 dB) in their sample of 33 children with unaided mild-to-profound UHL. The observation of a larger effect in co-located competing speech than SSN is opposite the finding in the present study.

The effect of UHL on performance when the TTS or SSN masker was spatially separated 90° to either side of the target stimulus differed according to masker type and masker location. The effect of UHL on $\mathrm{SRT}_{\mathrm{Ipsi\text{-}UHL}}$ was 5.3 dB in TTS and 1.9 dB in SSN. Values of $\mathrm{SRM}_{\mathrm{Ipsi\text{-}UHL}}$ were 4.4 dB (TTS) and 3.6 dB (SSN) for children with UHL, and 9.1 dB (TTS) and 3.9 dB (SSN) for children with NH. These results are similar to those of Corbin et al. (2017), who reported a significant effect of simulated UHL for $\mathrm{SRM}_{\mathrm{Ipsi\text{-}UHL}}$ in TTS but not in SSN. This is an important finding, as it suggests that the availability of binaural difference cues for speech recognition has different effects in TTS and SSN. The observation that UHL does not affect the $\mathrm{SRM}_{\mathrm{Ipsi\text{-}UHL}}$ in SSN suggests that the head-shadow effect is sufficient to account for the binaural benefit in this condition. The head shadow refers to the acoustic shadow cast by the head on the ear opposite a sound source. By virtue of the head shadow, the SNR at the NH ear of a child with UHL will be best when the masker is separated to the side ipsilateral the UHL. As a result, masked speech recognition improves relative to the condition when the masker is co-located with the target speech or contralateral the UHL. While the head-shadow effect accounts for the SRM observed in SSN, it does not fully account for the SRM observed in TTS. When TTS is ipsilateral to the UHL, SRM is 4.7-dB poorer for children with UHL than children with NH. This suggests that access to the signal at the ear with the less favorable SNR is important for SRM in TTS. This is consistent with a benefit of binaural squelch in TTS. Binaural squelch refers to the improvement in performance noted in the binaural condition as a result of access to ITDs in the target and masker signals (Bronkhorst & Plomp, 1988; Hawley et al., 2004; Levitt & Rabiner, 1967b).

As expected, based on previous studies, there was no benefit of spatially separating the masker to the side contralateral the UHL. As indicated by negative values of $\mathrm{SRM}_{\text{Contra-UHL}}$ in both TTS and SSN, separating the masker to the side contralateral the UHL actually degraded performance for most children with UHL. The average effect of UHL on $\mathrm{SRT}_{\text{Contra-UHL}}$ was 9.8 dB (TTS) and 6.3 dB (SSN), and the average effect of UHL on $\mathrm{SRM}_{\text{Contra-UHL}}$ was 9.2 dB (TTS) and 4.7 dB (SSN). The larger effect of UHL in the TTS relative to the SSN masker can be attributed to the inability of children with UHL to use binaural cues for a release from informational masking. This conclusion is supported by the fact that of the five children with UHL who achieved $\mathrm{SRM}_{\text{Contra-UHL}}$ >2 dB in TTS, three of them had unaided SII values ≥ 40.

There are few studies of masked speech recognition or SRM among children with permanent sensorineural or mixed UHL using maskers associated with informational masking. Results from the present study can be compared with those obtained by Reeder et al. (2015) and Griffin et al. (2018). Reeder et al. (2015) assessed speech recognition among 7- to 16-year-old children with moderately-severe to profound sensorineural UHL on numerous tasks. The task most comparable to that in the present study was spondee recognition in a single-talker male, single-talker female, or multi-talker speech masker presented at 0°, 90°, or -90° azimuth. Masker type varied during each trial to increase the uncertainty of the stimulus. Boxplots from Reeder et al. (2015) suggest an average SRM of 9 dB for children with NH, which is similar to the 9-dB SRM observed among the group of children with NH in the present study. For children with UHL, estimates of $\mathrm{SRM}_{\text{Ipsi-UHL}}$ and $\mathrm{SRM}_{\text{Contra-UHL}}$ are 7 dB and 0 dB, respectively (Reeder et al. 2015). These values can be compared with $\mathrm{SRM}_{\text{Ipsi-UHL}}$ and $\mathrm{SRM}_{\text{Contra-UHL}}$ values in TTS of 4.4 dB and -0.3 dB among the children with UHL in the present study. It is possible that the trial-to-trial uncertainty associated with the speech recognition task of Reeder et al. (2015) resulted in an increased amount of informational masking, and thereby greater values of SRM compared with the present study. It should be noted, though, that SRM was calculated in the study by Reeder et al. (2015) using average SRTs pooled across masker type. Therefore, it is not clear how masker type influenced SRM as a function of masker location.

Griffin et al. (2018) assessed SRM among 33 children ages 6 to 12 years with unaided, mild-to-profound sensorineural or mixed UHL. The SRT required for 50% correct recognition of sentences from the Hearing In Noise Test-Children (HINT-C; Nilsson, Soli, & Sullivan, 1994) was assessed in SSN and two-talker child babble (TTB). Target sentences were always presented from the front at 0° azimuth. Masker sentences were presented in four different conditions: (1) co-located with the target at 0° azimuth, (2) spatially separated 60° to the side ipsilateral the UHL, (3) spatially separated 60° to the side contralateral the UHL, and (4) spatially separated symmetrically at ±60°, so that one talker or SSN sample played simultaneously from each side of the participant. For children with UHL tested with asymmetric masker placement, values of $\text{SRM}_{\text{Ipsi-UHL}}$ were 4.7 dB (TTB) and 3.7 dB (SSN); values of $\text{SRM}_{\text{Contra-UHL}}$ were 0 dB (TTB) and -0.6 (SSN). These values are similar to the values observed in the present study for children with UHL. Among the control age-matched control group of children with NH, Griffin et al. (2018) reported SRM values of 5.1 dB (TTB) and 4.7 dB (SSN), respectively. Relative to the children with NH in Griffin et al. (2018), children with NH in the present study achieved average SRM values of 9.0 dB (TTS) and 3.7 dB (SSN). The discrepancy between results of these two studies could be due to differences in the amount of informational masking present in the stimuli. The target and masker speech in the present study consisted of speech from young adult females; as a result of acoustic and perceptual similarities, the potential for confusability between target and masker talkers was high. The potential for confusability between the target and masker stimuli used by Griffin et al. (2018) was relatively lower given that target speech was spoken by an adult male talker and masker speech was spoken by children. It is thus possible that SRM was reduced because there was less informational masking in the baseline condition in Griffin et al. (2018).

Degree of UHL

Recall that the majority (10/15) of children with UHL who participated in the present study had severe-to-profound UHL. That means that most of the children with UHL were essentially monaural listeners. Given that only 6 children had a value of SII > 5, it is difficult to draw conclusions regarding the effect of audibility in our dataset. Effects of UHL degree on our speech recognition task are most evident in $\text{SRM}_{\text{Contra-UHL}}$, where the performance difference between children with UHL and children with NH appears to be greater for children with SII < 5 than those with SII > 5. There was a trend in the present study for children with less severe degrees of UHL to achieve higher SRM, particularly in the Contra-UHL conditions, compared to children with SII < 5. This reflects their greater access to binaural difference cues when signals are presented above hearing thresholds.

Comparison to acute simulated conductive UHL. It was of interest to compare the results obtained from this cohort of children to those reported by Corbin et al. (2017) in children with acute conductive UHL. The degree, duration, and/or type of UHL across studies did not appear to affect $\text{SRM}_{\text{Ipsi-UHL}}$ in TTS or SSN. In both studies, $\text{SRM}_{\text{Ipsi-UHL}}$ was 4.2–4.4 dB in TTS and 3.6–3.9 dB in SSN. In contrast, $\text{SRM}_{\text{Contra-UHL}}$ was 2.8-dB and 1.1-dB lower in TTS and SSN for children with acute simulated UHL than those with longstanding permanent UHL. Group differences in SRTs for co-located maskers and spatially separated TTS account for the observed difference in $\text{SRM}_{\text{Contra-UHL}}$ between the two studies. In co-located TTS and SSN, SRTs were 2.3 dB and -2.2 dB for children with simulated UHL and 3.3 dB and -1.1 dB for children with permanent UHL. When TTS was spatially separated to the side contralateral the UHL, SRTs were 5.4 dB for children with simulated UHL and 3.6 dB for children with permanent UHL. The group difference in SRTs when TTS was spatially separated to the side contralateral the UHL could be the result of insufficient time to adapt to and/or reweight the recently disrupted binaural cues in the case of the acute simulated UHL (Kumpik et al., 2010). Evidence suggests that such adaptation and/or reweighting might take days to occur (Kumpik et al., 2010; Slattery & Middlebrooks, 1994). For the children with longstanding UHL, adaptation and/or reweighting would have occurred by the time of laboratory testing since UHL had been documented as stable for >6 months prior. It is also possible that children with simulated conductive UHL experienced less $\mathrm{SRM}_{\mathrm{Contra\text{-}UHL}}$ because of disrupted air- and bone-conduction interaural cues (Noble et al., 1994).

Hearing device use. General conclusions regarding the effect of hearing aid or CROS use on SRM cannot be drawn from the current dataset given that only four children completed the SRM task both with and without their personal hearing devices. However, among the three children who used a hearing aid, $\mathrm{SRM}_{\mathrm{Contra\text{-}UHL}}$ was negative in SSN, consistent with a detriment of target-masker separation on the azimuthal plane. In TTS, all three children who used amplification achieved 0.9 to 3.9 dB $\mathrm{SRM}_{\mathrm{Contra\text{-}UHL}}$ when using their hearing aid. All children who used hearing aids achieved $\mathrm{SRM}_{\mathrm{Ipsi\text{-}UHL}}$ in both maskers (range = 0.4 to 9.8 dB). These results should be interpreted with caution. For the child who used a CROS system, SRM decreased in all conditions. These effects are consistent with expectations based on the fact that the CROS effectively eliminates the benefit of head shadow due to microphone placement at the ear with UHL.

Effects of age on masked speech recognition and SRM

The child-adult difference in SRM for TTS was 2.2 dB in the present study and 2.6 dB in Corbin et al. (2017). Children and adults with NH showed greater SRM in TTS than in SSN. This pattern of results is consistent with literature demonstrating greater SRM for adults with NH under conditions associated with high informational as opposed to primarily energetic masking. Consistent with Corbin et al. (2017), there was a developmental effect of SRM in TTS, but not SSN, among participants with NH. These findings are consistent with results from other studies suggesting that SRM is not adult-like by 10 years of age (Cameron et al., 2006a, 2006b; Yuen & Yuan, 2014). It is possible that children's immaturity in their use of binaural cues, particularly in conditions associated with informational masking, is responsible for the developmental effect of SRM observed previously.

Relationship between SRM and parent report of functional communication challenges

At the outset we predicted a relationship between SRM in TTS and parents' ratings of their children's functional communication abilities on the APHAP; this expectation was based on the notion that SRM in the presence of informational masking reflects real-world communication abilities. Results showed a significant relationship between APHAP scores and $\mathrm{SRM}_{\text{Contra-UHL}}$ in TTS, but no significant association between APHAP scores and $\mathrm{SRM}_{\text{Contra-UHL}}$ in SSN or $\mathrm{SRM}_{\text{Ipsi-UHL}}$ in either masker. Children whose parents reported greater problems on the APHAP achieved less benefit from spatial separation when TTS was presented on the side of the better-hearing ear. This finding suggests that speech recognition in the most difficult target-masker spatial configuration (i.e., with TTS on the side of the ear with NH) was reflective of spatial hearing abilities in natural listening environments. A strong relationship between APHAP scores and $\mathrm{SRM}_{\text{Contra-UHL}}$ for TTS was predicted because $\mathrm{SRT}_{\text{Contra-UHL}}$ increases (worsens) as a result of a poorer SNR in addition to informational masking in the better-hearing ear. It is possible that SII could have mediated this association, in that greater degrees of hearing loss would reduce SRM in this condition and cause more communication difficulties. This possibility is moderated somewhat by the finding of a non-significant association between APHAP scores and SII.

Factors such as age at identification of UHL and/or fitting of amplification, use of assistive technology in the classroom, comorbid medical and/or developmental delays or diagnoses, maternal level of education, family and caregiver characteristics, and utilization of specialized educational services (e.g., Individualized Educational Plan or 504 Plan) could influence the results obtained in the present study (e.g., Ambrose, Walker, Unflat-Berry, Oleson, & Moeller, 2015; Moeller et al., 2016; Tomblin, Oleson, Ambrose, Walker, & Moeller, 2014; Yoshinaga-Itano, Sedey, Wiggin, & Chung, 2017). Unfortunately, the relatively small sample size limited our ability to draw conclusions about the effects of these factors in the present dataset.

Conclusions and future directions

Results from the present study add to the growing body of literature exploring the specific auditory deficits experienced by children with UHL. The present findings challenge the notion that NH in one ear is sufficient for communication in complex listening environments. One of the motivations behind this study was the possibility that clinical assessment of spatial hearing abilities would inform clinical management in this population. Results from the correlational analyses suggest that real-world communication abilities are associated with SRM. However, the extent to which this relationship is predicted by audibility is unclear given that 9/15 children with UHL had an SII value of <5 in the affected ear. Future studies involving a greater number of children with more variable values of SII in the affected ear may be more informative in this regard. If spatial hearing and subjective report of listening difficulties are not fully predicted by the audiogram, results obtained from an assessment of SRM could provide new information regarding the functional auditory performance of children with UHL in their natural listening environments. This new information would guide clinical management of pediatric UHL on an individual basis.

CHAPTER 4: CONCLUSIONS AND FUTURE DIRECTIONS

The experiments reported in this dissertation addressed the spatial hearing deficits experienced by children with unilateral hearing loss (UHL) in three paradigms: auditory localization, spatial release from masking, and functional listening abilities as assessed by parent report.

The effect of UHL on children's spatial release from masking (SRM) in two-talker speech (TTS) and speech-shaped noise (SSN)

Chapter 2 described the consequences of simulating a moderate conductive UHL in school-age children and adults with normal bilateral hearing. An earplug and earmuff were used to create a simulated UHL. Participants served as their own controls, completing the experiment both with and without the acute simulated UHL (simulated UHL and NH conditions, respectively). Thresholds for 50%-correct sentence recognition were assessed in TTS and SSN under three different target-masker configurations. Target sentences always originated from the front of the listener. Masker stimuli were presented co-located with the target speech (0°) or spatially separated to +90° or -90° azimuth. The benefit derived from spatially separating the target and masker stimuli was quantified as SRM. For each masker, SRM was calculated as the difference in SRTs obtained when the target and masker were co-located and when the masker was spatially separated to +90° or -90° azimuth. Three values of SRM were calculated in each masker: one to represent the benefit of spatially separating the masker to either side in the no-plug condition ($\mathrm{SRM}_{\text{no-plug}}$), one to represent the benefit of spatially separating the masker to the side ipsilateral the simulated UHL ($\mathrm{SRM}_{\text{Ipsi-UHL}}$), and another to represent the benefit of spatially separating the masker to the side contralateral the simulated UHL ($SRM_{Contra\text{-}UHL}$). The hypothesis was that UHL negatively impacts masked speech recognition, particularly under conditions in which binaural difference cues facilitate segregation of target and masker stimuli. Therefore, the consequences of UHL were expected to be greatest when the target and masker stimuli were separated in space and when the masker was TTS.

In the No-plug condition, SRM was significantly larger in the TTS than the SSN masker. This finding is consistent with data from previous studies of adults (Arbogast et al., 2002; Freyman et al., 2001). Relative to the No-plug condition, $SRM_{Ipsi\text{-}UHL}$ was essentially unchanged in the SSN. However, $SRM_{Ipsi\text{-}UHL}$ was markedly reduced in the TTS relative to the No-plug condition. In both the TTS and SSN, $SRM_{Contra\text{-}UHL}$ was negative, meaning that spatial separation of target and masker was detrimental to performance. Similar to the difference between $SRM_{No\text{-}plug}$ and $SRM_{Ipsi\text{-}UHL}$, the difference between $SRM_{No\text{-}plug}$ and $SRM_{Contra\text{-}UHL}$ was greater in TTS than SSN. The conclusion from this first study was that disrupted binaural difference cues affect spatial hearing in different ways according to masker type and masker location (e.g., ipsilateral or contralateral to the simulated UHL).

While Chapter 2 provides information about the effect of an acute simulated conductive UHL, the findings do not indicate how permanent, sensorineural or mixed UHL affect SRM in the two maskers. As a result of neuroplasticity and/or learned compensatory strategies, children with longstanding UHL may learn to use cues that improve their performance relative to children with temporary UHL when audibility is matched across groups. There are also important differences to be considered with regard to conductive versus sensorineural UHL. In both cases, auditory signals are increasingly attenuated as the magnitude of hearing loss increases. In the case of sensorineural hearing loss, the auditory signal is encoded and carried by a damaged auditory pathway (at the level of the cochlea and/or neural auditory system), which is thought to introduce distortion in addition to attenuation. As a result, children with sensorineural UHL may exhibit poorer performance than the children with conductive UHL.

Chapter 3 described results from a separate cohort of participants that included children with permanent sensorineural or mixed UHL, age-matched peers with NH, and adults with NH on the same SRM task described in Chapter 2; conductive UHL was not simulated. Among the group of children with permanent sensorineural or mixed UHL, the majority had profound UHL. Consistent methods across the two chapters facilitated a comparison between the effects UHL duration (acute versus longstanding), type (conductive versus sensorineural or mixed), and degree (moderate versus profound) on SRM in the two maskers. Results were largely similar to those obtained in Chapter 2. Among participants with NH, SRM was greater in TTS than SSN for children and adults; the average child-adult difference in SRM was 2 dB for TTS and <0.5 dB for SSN. The detriment of listening with impoverished binaural difference cues (i.e., permanent sensorineural or mixed UHL) differed according to masker type and masker location. When the masker was located ipsilateral to the UHL, there was a benefit of target-masker separation for speech recognition (represented by $\mathrm{SRM}_{\mathrm{Ipsi\text{-}UHL}}$). The detriment of separating the masker to the side contralateral the UHL was greater in TTS than SSN, but differed across the two studies. For TTS and SSN maskers contralateral to the UHL, values of SRM were -3.1 dB and -2.3 dB for children with simulated UHL; this can be compared with values of -0.3 and -1.1 dB for children with permanent UHL. The difference in SRM observed between children with NH in the No-plug and simulated UHL conditions was 11.7 dB (TTS) and 6 dB (SSN) when maskers were contralateral to the UHL; this can be compared with differences of 9.2 dB (TTS) and 4.7 dB (SSN) between children with NH and children with permanent UHL. Together, results from these studies suggest that: (1) there is a developmental effect of SRM in TTS for participants with NH, (2) the spatial hearing deficits experienced by children with UHL on SRM tasks differ according to the type and location of competing maskers, and (3) duration, type, and/or degree of UHL impacts the magnitude of spatial hearing deficits observed in children with UHL. This new information may guide the development of future clinical assessments of masked speech recognition abilities in children with UHL.

Future directions. Many of studies examining speech recognition among children with UHL (Bess et al., 1986; Bovo et al., 1988; Kenworthy et al., 1990) have done so in "monaural direct (MD)" and "monaural indirect (MI)" conditions, which do not facilitate a calculation of SRM. In monaural direct and indirect conditions, one loudspeaker is located 45° from midline on the side ipsilateral the ear with UHL, and another loudspeaker is located 45° from midline on the side contralateral the ear with UHL. In the MD condition, the target is routed to the loudspeaker contralateral the UHL (i.e., on the side of the NH ear), and the masker (often multi-talker babble, cafeteria noise, or SSN) is routed to the loudspeaker ipsilateral the UHL. In the MI condition, this configuration is switched so that the target is ipsilateral to the UHL, and the masker is contralateral to the UHL. Due to the head shadow effect, performance in the MD condition is thought to reflect the best-case listening scenario, while performance in the MI condition is thought to reflect the worst-case listening scenario.

Current classroom recommendations and counseling for children with UHL are based on results from MD/MI studies. Findings from the present study, Griffin et al. (2018), and Reeder et al. (2015) suggest that results from studies utilizing MD and MI configurations may underestimate the difficulties children with UHL face in listening environments containing substantial informational masking. Specifically, the head shadow effect is not sufficient for children with UHL to achieve masked speech recognition levels on par with their NH peers. Counseling regarding realistic expectations for communication in environments with competing speech (e.g., the car, classroom, or dinner table) should incorporate this information.

A large-scale, multi-center study of the factors contributing to observed variability in developmental outcomes among children with UHL is needed. Enrollment of children with UHL across multiple study sites would ensure a large number of heterogeneous children with varying degrees of UHL. Future studies examining the spatial hearing abilities among children with UHL might involve presentation of target speech in front of the listener and masker stimuli from the front, both sides (Griffin et al. 2018), or around the listener (Kenworthy et al., 1990; Reeder et al. 2015; Ruscetta et al. 2005). Symmetrical placement of maskers is appealing because it minimizes the contribution of consistent improvements in signal-to-noise ratio (SNR) afforded by the head-shadow. As a result, SRM for symmetrically placed maskers is more reflective of the ability to binaurally process target speech during epochs of relatively advantageous SNRs, which vary between the ears.

There has been no investigation into the effect of the masker talker’s head orientation relative to the listener on SRM in children with UHL. Prior investigations of speech recognition in spatially separated maskers test listeners while they are directly facing the listener. In realistic conversational settings, masker talkers are often not directly facing the listener. Recent studies of masked speech recognition in children and adults with NH suggest that masker talker orientation affects the magnitude of SRM observed, particularly for asymmetrically placed maskers (Corbin et al., 2019). Under these conditions, SRTs when the target and masker are co-located are lower when the masker talker is oriented away from the listener compared to facing the listener. This benefit is a result of the unmasking of the extended high-frequency content of target speech. In contrast, SRTs are less affected by masker head orientation when the target and masker are spatially separated. It would be of interest to investigate the extent to which masker facing orientation affects the results obtained in the TTS masker of the present study. It is likely that SRM in children with NH would be lower with maskers oriented away from the listener. If this is the case, then the effect of UHL on SRM in TTS could have been overestimated in the present study due to the (unrealistic) assumption that the masker talker is always facing the listener.

Localization on the azimuthal plane in children with permanent sensorineural or mixed UHL.

As described in Chapter 3, the same participants who completed the SRM task also completed localization testing. The localization task was modeled after a previous study of localization abilities among adults with profound UHL (Dorman et al., 2015). Participants sat in the center of an 11-speaker arc that spanned 180° azimuth. The participant faced the loudspeaker located directly in front at 0° azimuth and was instructed to indicate the source location of a stimulus presented from one of the eleven loudspeakers, chosen at random. Pink noise bursts were filtered to create three separate stimuli: full spectrum (all-pass, AP; 125–6000 Hz), low-pass (LP; 125–500 Hz), and high-pass (HP; 1500–6000 Hz). Participants completed one run for each stimulus (AP, LP, and HP), and a fourth run in which the stimuli were randomly intermixed. Each run consisted of 33 trials, with the stimulus presented from each speaker a total of three times. Absolute localization of sound sources was quantified as root-mean-square (RMS) error in degrees. The rationale for this approach was that listeners' relative use of binaural difference and monaural cues can be inferred from performance on localization tasks involving filtered stimuli. The LP and HP stimulus conditions facilitate assessment of performance when cues to source location are predominantly low-frequency ITDs or high-frequency ILDs, respectively. In the Mixed condition, the variable and unpredictable nature of the stimulus spectrum renders monaural spectral shape cues to azimuthal location unreliable. The hypothesis was that the wide range of localization abilities among children with UHL is due to individual differences in the relative use of binaural difference and monaural cues to location. Children with less severe UHL were expected to perform better overall than children with more severe UHL due to greater access to binaural difference cues.

Among the participants with NH, children performed significantly more poorly than adults. For NH children and adults, the AP condition was easiest, followed by the HP, Mixed, and LP conditions. For children with UHL, performance was poorer and individual differences were more pronounced compared to children with NH. As expected, children with less severe UHL performed more like their peers with NH. Among children with UHL who had SII values of <5, performance in the LP and Mixed conditions tended to be worse than that in the AP and HP conditions. These results provide preliminary support the following conclusions: (1) sound source localization improves with increasing age among children with NH, and (2) at least some children with severe-to-profound UHL appear to rely on monaural spectral shape cues to localize sounds on the azimuthal plane.

Future directions. Future investigations involving a larger number of children with greater variability in age and UHL degree would shed light on the conditions under which children with UHL use monaural spectral shape cues. It is possible monaural spectral shape cues are only used in cases of severe-to-profound UHL, or after a certain time point in development. Evidence for a developmental effect of the ability to use monaural spectral shape cues comes from Johnstone et al. (2010). Among the cohort of children with UHL tested in that study, children ages 6 to 9 years were fit with hearing aids by the age of 5 years and benefited from amplification. Children ages 10 to 14 years, who were not fit with amplification until 7 years of age, did not benefit from amplification. Importantly, the unaided performance of children ages 10 to 14 years was better than the aided performance of children ages 6 to 9 years, regardless of UHL degree. These findings from Johnstone et al. (2010) suggest that the localization abilities among children with UHL improve with age in the absence of amplification, perhaps the result of learning how to use monaural spectral shape cues over time.

Functional listening abilities as assessed by parent report of children with UHL.

As described in Chapter 3, parents of children with sensorineural or mixed UHL completed the SSQP (Galvin & Noble, 2013) and the Background Noise (BN) and Ease of Communication (EC) subscales of the APHAP (Kopun & Stelmachowicz, 1998). The SSQP contains three subscales (Speech, Spatial, and Qualities) designed to query children's spatial hearing abilities in a variety of listening situations. The SSQP was administered according to the test manual, which instructs parents to observe certain aspects of their child's behavior a week prior to completing the questionnaire. The inclusion of observation periods required parents to complete the SSQP at home before or after visits to the lab. The BN and EC subscales of the APHAP were administered to parents in the lab while their child was completing the SRM and localization tasks described above. The BN subscale measures the child's ability to understand speech in the presence of multiple talkers or competing noise, while the EC subscale reflects the effort a child expends to communicate under relatively easy listening conditions. The scores from the BN and EC subscales were averaged to obtain a composite APHAP score for each child.

Correlational analyses were conducted to examine the relationship between children's SRM and their scores on the APHAP. The rationale behind this approach was twofold: (1) in children with bilateral sensorineural hearing loss, speech recognition in TTS, but not SSN, is associated with parent's reports of their everyday communication difficulties (Hillock-Dunn et al., 2015); and (2) SRM in complex speech maskers reflects adults' performance in real-world environments and provides insight into factors that contribute to individual differences in masked speech recognition (Phatak et al., 2018; Swaminathan et al., 2015). The hypothesis was that SRM in the presence of TTS would capture the individual differences that affect children's performance in real-life listening situations. Parent's reports of their children's functional listening abilities were expected to strongly correlate with SRM in TTS. More modest correlations were expected for SRM in the noise masker. Lower scores on the APHAP were expected for children who had greater audibility in the ear with UHL, represented by the unaided speech intelligibility index (SII) value calculated for a 75 dB SPL speech input in that ear.

Statistical analyses were not conducted on the data for the SSQP because many parents failed to return part or all of this questionnaire; only 12/15 SSQP Speech subscales and 9/15 each of the SSQP Spatial and Qualities subscales were returned. However, visual inspection of these data did not indicate a reliable relationship between SSQP scores and SRM in either masker. Perhaps a relationship would emerge with a larger sample size of children with a more uniform distribution of degrees of UHL (i.e., an equal number of children with mild, moderate, severe, and profound UHL).

Results from the correlational analyses involving the APHAP were consistent with a statistically significant relationship between APHAP scores and $\text{SRM}_{\text{Contra-UHL}}$ for TTS, but no relationship as observed for the $\text{SRM}_{\text{Contra-UHL}}$ in SSN. The correlations between APHAP scores and the $\text{SRM}_{\text{Ipsi-UHL}}$ did not approach significance for either masker. These results suggest an association between APHAP scores and spatial hearing abilities when assessed in the most difficult listening conditions (i.e., TTS on the side of the ear with NH). A non-significant trend for a relationship between RMS localization error in the AP condition and APHAP scores further supports an association between spatial hearing abilities and parent ratings on the APHAP.

Future directions. Additional data are needed to support behavioral assessments of spatial hearing abilities among children with UHL as a proxy of functional auditory performance in everyday listening environments. One way to confirm that SRM provides clinical insight into the real-world communication abilities of children with UHL is to assess performance with a greater number of children across a wider range of ages, with varying degrees of UHL. Future investigations might also involve measures of working memory, attention, and auditory comprehension. These abilities are known to predict masked speech recognition in children with hearing loss (Klein et al., 2017). Including measures of those abilities in a statistical model predicting SRM could clarify the role of peripheral effects related to the severity of UHL.

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