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Spatial Hearing as a Function of Presentation Level in Moderate-to-Severe Unilateral Conductive Hearing Loss

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Abstract

Hypothesis: Patients with moderate-to-severe unilateral conductive hearing loss (UHL) can make use of binaural difference cues when stimuli are presented at a high enough intensity to provide audibility in the affected ear.

Background: Spatial hearing is essential for listening in complex environments and sound source localization. Patients with UHL have decreased access to binaural difference cues, resulting in poorer spatial hearing abilities compared to listeners with normal hearing.

Methods: Twelve patients with moderate-to-severe UHL, most due to atresia (83.3%), and 12 age-matched controls with normal hearing bilaterally participated in this study. Outcome measures included: (1) spatial release from masking (SRM), and (2) sound source localization. Speech reception thresholds (SRTs) were measured with target speech (Pediatric AzBio sentences) presented at 0° and a two-talker masker that was either co-located with the target (0°) or spatially separated from the target (symmetrical, ±90°). SRM was quantified as the difference between SRTs in these two conditions. Localization ability in the horizontal plane was assessed in a 180° arc of eleven evenly-spaced loudspeakers. These two tasks were completed at 50 and 75 dB SPL.

Results: Both children and adults with UHL performed more poorly than controls when recognizing speech in a spatially separated masker or localizing sound; however, this group difference was larger at 50 than 75 dB SPL.

Conclusion: Patients with UHL experience improved spatial hearing with the higher presentation level, suggesting that the auditory deprivation associated with a moderate-to-severe UHL does not preclude exposure to – or use of – binaural difference cues.

INTRODUCTION

Spatial hearing is essential in everyday situations such as listening to speech in noisy environments or localizing sources of sound. A classic example of this is the ‘cocktail party effect,’ where an individual must focus on an intended target despite the additional presence

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of unwanted environmental maskers (e.g., in a noisy restaurant or classroom)(1). The ability to navigate and communicate in complex, three-dimensional soundscapes has important implications for development, learning, and safety.

Patients with unilateral conductive hearing loss (UHL), even a mild UHL, are known to have poorer spatial hearing than those with normal hearing (NH) due to decreased access to binaural difference cues(2,3). In children, permanent sensorineural unilateral hearing loss has been shown to negatively impact language abilities, speech and psychosocial development, and academic performance despite NH in the contralateral ear(4,5). Similar deficits have also been shown in those with moderate-to-severe UHL, including patients with aural atresia(6–8).

Spatial hearing depends on monaural and binaural spatial cues that help the listener identify source location and attend to the target of interest. Monaural cues are present in each ear individually. An example is the spectral shaping of the auditory signal as it enters the pinna and external ear canal(9). It is unclear the extent to which listeners with NH make use of monaural cues for localization on the horizontal plane(9). Binaural cues include interaural time differences (ITDs), which are available at low frequencies, and interaural level differences (ILDs), which are available at high frequencies(2,9,10). UHL precludes a benefit from binaural cues, as reduced audibility in the affected ear may limit access to binaural stimulation.

Two aspects of spatial hearing that utilize binaural cues are spatial release from masking (SRM) and sound localization. SRM is the difference in speech recognition performance when the target and masker are co-located, compared to when they are spatially separated(2,11,12). In SRM, binaural difference cues allow listeners to attend to the audible speech information that is present across frequency in the two ears, thus improving speech recognition. SRM has been observed in children as young as two years of age, although the age associated with mature performance varies based on characteristics of the listening task(13).

Sound localization is the ability to accurately locate a sound source relying solely on auditory cues, such as interaural time and level differences for low and high frequency sounds, respectively. For example, a low frequency stimulus reaching the right ear prior to reaching the left ear will be localized to the right side. Likewise, a high frequency sound reaching the left ear at a greater intensity than the right ear will be localized to the left side. To some extent, localization abilities are evident a few hours after birth in newborns with NH(14). In simple listening conditions, this ability can approach adult-like levels around 5–6 years of age(13).

Early auditory deprivation in one ear, such as that associated with congenital unilateral aural atresia, can result in aural preferences and delays in binaural processing that are largely irreversible(9,15–17). Unilateral auditory deprivation limits stimulation of sensory afferents, potentially affecting cortical organization and future ability to utilize binaural cues(15,16,18); use of a bone conduction hearing aid could provide stimulation to the impaired ear, but it would not restore access to natural binaural cues. A period of time when

stimulation is required for typical development is sometimes described as a ‘sensitive period’(19). Although the timing and degree of auditory deprivation associated with the sensitive period for binaural hearing is currently unknown, temporary deficits in binaural processing have been seen as a result of transient mild-to-moderate conductive hearing losses in children with otitis media(16,20).

The objective of this study was to evaluate spatial hearing abilities in children and adults with permanent moderate-to-severe UCHL. We wanted to investigate if this type of hearing loss precludes the development of spatial hearing abilities, or whether spatial hearing is possible when stimuli are presented at a high enough level to provide some audibility in the affected ear. Good spatial hearing under these conditions would suggest that the auditory deprivation associated with congenital moderate-to-severe UCHL does not preclude development of binaural auditory pathways.

MATERIALS AND METHODS

Participants

There were two groups of participants: 12 participants with UCHL and 12 participants with NH. Pure-tone detection thresholds were evaluated at octave frequencies from 250 to 8000 Hz(21). Participants with hearing loss had air-conduction thresholds of 30 dB HL or less in one ear and 40 dB HL or greater in the other, with air-conduction pure-tone averages (500, 1000, 2000, and 4000 Hz) >50 dB HL. Masked bone conduction thresholds were 25 dB HL or better bilaterally. Control participants were age-matched to UCHL participants to within 6 months and had air-conduction thresholds of 20 dB HL or less bilaterally, except for the oldest participant. Thresholds for this individual were 35 dB HL or better at all tested frequencies in both ears. For Spanish/English bilingual participants, the Bilingual Input-Output Survey (BIOS) was used to identify control participants of similar language profiles. There were six pairs of participants who were bilingual. Inclusion criteria included meeting audiometric criteria, age >5 years, self-reported English speaker, and ability to repeat spoken phrases. Exclusion criteria included previous ear canal reconstruction. Informed consent was obtained from participants or their parents prior to the hearing screen and subsequent enrollment in the study. Although the two adult participants with acquired hearing loss were not included in the statistical analysis below, their data are valuable for comparison to those with congenital atresia. Better performance for adults with acquired moderate-to-severe UCHL compared to congenital loss could indicate an important role for prior exposure to binaural cues in the development of binaural hearing.

Spatial Release from Masking

Masked sentence recognition with and without spatial cues was evaluated using Pediatric AzBio sentences(22). This corpus was constructed based on utterances produced by native English-speaking 5- to 12-year-olds, and it includes 16 lists of 20 sentences. The target talker is an adult female (mean F0 of 230 Hz). As in Calandruccio et al. (2014), the masker was two female talkers (mean F0 of 170 and 210 Hz) reading excerpts from *Jack and the Beanstalk*(23,24). One talker began reading the story from the first page, while the other began reading from the middle of the story. Silences longer than 300 ms were reduced to

approximately 200 ms. Each recording was then RMS normalized, and the two recordings were combined to a single track. Using 100-ms raised-cosine ramps, maskers were gated on 500 ms before the beginning of the target sentence and off 500 ms after completion of that sentence.

All target sentences were presented directly in front of the listener, at 0°. The two-talker masker was either co-located with the target (0°) or it was spatially separated from the target, with one voice at +90° and the other at -90°; the stimulus was presented at an overall level (target+masker) of either 50 or 75 dB SPL. This resulted in four conditions (two positions x two levels). Participants heard 40 sentences from two randomly selected lists in each listening condition. All words in the target sentences were scored by a trained examiner using a custom MATLAB script. The SRT associated with 50% correct was estimated using two interleaved 1-down/1-up adaptive tracks, one using a lax criterion and one using a strict criterion. For odd-numbered trials, a response was considered “correct” if one or more words in the sentence was repeated correctly. For even numbered sentences, a response was considered “correct” if all words or all but one word in the sentence was repeated correctly. Based on these rules, the SNR was decreased following a correct response and increased following an incorrect response; these level adjustments were initially made in steps of 8 dB SPL, and steps were reduced by a factor of two following the first two track reversals. This procedure results a sampling of performance across a broad range of the psychometric function. A two-parameter logit was fit to the word-level data obtained for each participant in each condition, and the final estimate of SRT was the 50% point on that function.

Localization

Auditory localization was evaluated using a 200-ms burst of pink noise, bandpass filtered 126–6000 Hz (48-dB/octave) and gated on and off using 20-ms raised-cosine ramps. The nominal stimulus level was either 50 or 75 dB SPL, with the actual level roved ± 5 -dB relative to the nominal level based on a random draw from a uniform distribution. The purpose of the level rove was to limit accuracy of responses based solely on the stimulus level in one ear. The listener’s task was to verbally indicate the source location. Loud speakers were labeled with numbers or pictures of animals, depending on the listener’s age and/or preference. A recording of the word “Ready,” spoken by a male talker, was presented from the center loudspeaker immediately prior to each stimulus presentation. This was done to remind the participant to face the center loudspeaker and indicate that a trial was about to begin. 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. Absolute localization error was quantified as RMS error in degrees.

General procedures

Testing was completed in a double-walled sound-treated booth (10' x 10') 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 arc, equidistant from each speaker and facing the middle speaker (0°). Chair height was adjusted individually such that the participant’s ears were on the same plane as the speaker cones. Each loudspeaker is

connected to one channel of a 24-channel soundcard (MOTU 24i, Cambridge, MA) through a balanced line. The soundcard is controlled via USB by a computer running MATLAB (MathWorks, Natick, MA) and using functions from the Psychtoolbox(25). Stimuli were calibrated using a microphone suspended from the booth ceiling, at the center of the arc and level with the loudspeaker cone.

Test sessions required approximately 2 hours with rest breaks in between listening conditions. All participants were paid \$15/hr. This study was approved by the Biomedical Institutional Review Board at The University of North Carolina at Chapel Hill.

RESULTS

Demographics

Demographic information for the UCHL group is shown in Table 1. This group included 4 adults (ages 19.7–61.1 yrs, 2 males) and 8 children (ages 6.2–14.5 yrs, 4 males). Participants with NH included 4 adults (ages 20.2–61.3 yrs, 2 males) and 8 children (ages 6.1–15 yrs, 3 males). The most common etiology of UCHL was congenital atresia (10 participants). Audiograms of subjects are shown in Figure 1. Seven of the participants had previous experience with hearing amplification, with 4 using a bone-anchored hearing aid (BAHA), and 3 using a softband BAHA. The statistical analyses reported below include only those participants with congenital atresia and their normally-hearing age-matches; including participants with acquired hearing losses did not change the pattern of significance, however.

Spatial Release from Masking

Results for the speech recognition task are shown on the bottom row of Figure 2. Mean spatial release from masking for NH participants was 7.4 dB at 50 dB SPL and 8.2 dB at 75 dB SPL. In the UCHL group, mean spatial release from masking was 0.3 dB at 50 dB SPL and 2.5 dB at 75 dB SPL. A rmANOVA was conducted to evaluate the effects of conductive hearing loss and level on spatial release from masking. Results revealed significant main effects of hearing loss ($F(1,18) = 69.25, p < .001$) and presentation level ($F(1,18) = 6.41, p = .021$). There was no significant interaction ($F(1,18) = 1.49, p = .238$). For NH participants, there were no effects of age on performance at 50 or 75 dB HL ($r(10) = -.36, p = .314$; $r(10) = -.37, p = .292$). For UCHL participants, spatial release from masking increased significantly with age at 50 dB SPL ($r(10) = -.83, p = .003$) but not at 75 dB SPL ($r(10) = -.10, p = .779$).

Theoretically, smaller values of SRM in participants with UCHL could be due either to poorer SRTs when the target and masker are spatially separated, or to better SRTs when the target and masker are co-located. The SRT data (not shown) provide support for the former possibility. The effect of UCHL on SRTs was estimated by computing the difference between SRTs for each UCHL participant and their age-matched NH control. For all four conditions, participants with UCHL performed more poorly on average than those with NH. For the co-located target and masker, the mean group difference was 3.5 dB for both the 50- and 75-dB-SPL levels ($t(9) = 5.13, p < .001$; $t(9) = 3.88, p = .004$). For the spatially

separated target and masker, the mean group difference was 10.6 dB at 50 dB SPL ($t(9) = 9.30, p < .001$) and 9.1 dB at 75 dB SPL ($t(9) = 6.85, p < .001$).

Localization

Results for the localization task are shown on the top row of Figure 2. The RMS localization error for NH participants was 6.6° at 50 dB SPL and 6.5° at 75 dB SPL. In the UCHL group, RMS localization error was 51.3° at 50 dB SPL and 20.2° at 75 dB SPL. At the higher level, all participants in the UCHL group were performing better than chance (57°)(26). A repeated-measures analysis of variance (rmANOVA) was conducted to evaluate the effects of conductive hearing loss and presentation level on RMS error. A log transformation was applied to values of RMS error to normalize variance across groups. Results revealed significant main effects of hearing loss ($F(1,18) = 93.59, p < .001$) and level ($F(1,18) = 23.85, p < .001$). A significant interaction was observed ($F(1,18) = 23.41, p < .001$). Overall RMS was also evaluated as a function of age for each group and at each presentation level; a log transformation was applied to age due to the expectation of more rapid development in younger listeners. For the NH group, there were no significant effects of age at either level ($t(10) = .51, p = .133$; $t(10) = -.62, p = .055$). For the UCHL group, localization ability improved significantly with age at 50 dB SPL ($t(10) = -.90, p < .001$) but not at 75 dB SPL ($t(10) = -.12, p = .744$).

Stimulus Audibility—Stimulus audibility in the ear with UCHL was evaluated by computing the long-term magnitude spectrum of the speech target and computing the stimulus level for equivalent rectangular bandwidths centered on each octave frequencies 125–8000 Hz(27). These levels were transformed from dB SPL to dB HL and compared to audiometric thresholds for ears with UCHL. This comparison indicates that none of the participants had audibility in their impaired ear at the 50-dB-SPL stimulus level. About half of them had some limited audibility at the 75-dB-SPL level. However, this analysis is limited by the fact that the long-term average power spectrum does not fully capture audibility of the speech itself, which is characterized by marked fluctuations in level.

DISCUSSION

The aim of the current study was to determine if permanent moderate-to-severe UCHL precludes the development of spatial hearing abilities and the use of binaural cues. For both localization and spatial release from masking measures there was a significant improvement in SRM seen in the UCHL group when increasing the presentation level from the 50 dB SPL to 75 dB SPL. Though performance did not reach levels seen in the NH group, the improvement in performance indicates that participants with moderate-to-severe UCHL are able to utilize binaural cues when provided with sufficient audibility in the affected ear to overcome the hearing loss. This could indicate that the auditory deprivation associated with congenital moderate-to-severe UCHL does not preclude development of binaural auditory pathways. Stimulation of sensory afferents via self-generated noise or loud environmental stimuli may be sufficient to develop spatial hearing abilities to some degree. This possibility receives additional support from the observation of similar performance for adult participants with acquired vs congenital moderate-to-severe UCHL, with the caveat that

there were only two adults with acquired UCHL in the present study. The 3-dB higher SRTs for participants with UCHL than NH could be due, at least in part, to the lack of binaural summation in participants with UCHL(28).

There were large individual differences at the 50 dB SPL presentation level for both localization and spatial release from masking in participants with UCHL. Performance ranged from near the normal range to near chance. One interesting finding was the effect of age on performance at 50 dB SPL, with some evidence of increasing SRM with increased age. It is possible that subtle cues, such as monaural spectral cues, are required to perform well at this low presentation level, and the auditory abilities required to take advantage of these cues develops over the age range evaluated in the present study.

Performance in both localization and spatial release from masking tasks was better at the higher presentation level. One clinical implication of this relates to hearing rehabilitation of those with UCHL. For patients with aural atresia, bone conduction hearing aids and middle ear implants have been suggested as primary methods for hearing rehabilitation(29–31). Though not performed in any of the participants in the current study, surgical correction of atresia is also an option in select patients, with variable outcomes in postoperative hearing(29–34). The current study demonstrates the importance of improving audibility for patients with moderate-to-severe UCHL and its possible impact on spatial hearing. The possibility of obtaining binaural benefit suggests that providing ear-specific stimulation may be an advantage in this population.

CONCLUSION

Patients with permanent moderate-to-severe UCHL experience improved spatial hearing including sound source localization and spatial release from masking with higher presentation levels, suggesting that the auditory deprivation associated with a moderate-to-severe UCHL does not preclude exposure to – or use of – binaural difference cues.

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Figure 1:
Air-conduction thresholds for individual listeners with UCHL. Dark lines and circles show mean and standard deviations for thresholds in the normal ear (top) and the impaired ear (bottom).

Figure 2:

Localization error (top) and spatial release from masking (bottom). The left column shows the distribution of results for each presentation level. The middle and right columns show results as a function of age for the 50 and 75 dB SPL levels, respectively. Open circles show results for listeners with congenital moderate-to-severe UCHL, and circles with crosses indicate those with acquired UCHL. Stars indicate results for age-matched NH controls.

Table 1:

Demographic information on participants with unilateral conductive hearing loss (UCLH).

UCLH number	Sex	Age	Side	Onset (yrs)	Etiology	BC-PTA (dB HL)	AC-PTA (dB HL)	Previous treatment
1	F	6.2	R	Congenital	Atresia	3.75	55	
2	F	7.5	L	Congenital	Atresia	6.25	66.25	Softband BAHA
3	M	8.6	L	Congenital	Atresia	7.5	60	Softband BAHA
4	M	8.8	R	Congenital	Atresia	8.75	58.75	
5	F	9	L	Congenital	Atresia	12.5	70	Softband BAHA
6	M	9.8	L	Congenital	Atresia	8.75	67.5	
7	M	12.3	L	Congenital	Atresia	8.75	62.5	
8	F	14.5	R	Congenital	Atresia	12.5	78.75	BAHA
9	F	19.7	L	Congenital	Atresia	11.25	70	
10	M	22	L	Congenital	Atresia	13.75	70	BAHA
11	F	23.2	R	Acquired (5)	Cholesteatoma	17.5	82.5	OCR, canal wall down tympanomastoidectomy, BAHA
12	M	61.1	R	Acquired (29)	Chronic otitis media	12.5	55	BAHA

BC-PTA: Bone Conduction Pure-Tone Average (500, 1000, 2000 and 4000 Hz)

AC-PTA: Air Conduction Pure-Tone Average (500, 1000, 2000 and 4000 Hz)

BAHA: Bone-Anchored Hearing Aid

OCR: Ossicular Chain Reconstruction