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Research Paper

The effect of simulated unilateral hearing loss on horizontal sound localization accuracy and recognition of speech in spatially separate competing speech

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A B S T R A C T

Unilateral hearing loss (UHL) occurs in 25% of cases of congenital sensorineural hearing loss. Due to the unilaterally reduced audibility associated with UHL, everyday demanding listening situations may be disrupted despite normal hearing in one ear. The aim of this study was to quantify acute changes in recognition of speech in spatially separate competing speech and sound localization accuracy, and relate those changes to two levels of temporary induced UHL (UHL_{30} and UHL_{43}; suffixes denote the average hearing threshold across 0.5, 1, 2, and 4 kHz) for 8 normal-hearing adults. A within-subject repeated-measures design was used (normal binaural conditions, UHL_{30} and UHL_{43}). The main outcome measures were the threshold for 40% correct speech recognition and the overall variance in sound localization accuracy quantified by an Error Index (0 = perfect performance, 1.0 = random performance). Distinct and statistically significant deterioration in speech recognition (2.0 dB increase in threshold, $p < 0.01$) and sound localization (Error Index increase of 0.16, $p < 0.001$) occurred in the UHL_{30} condition. Speech recognition did not significantly deteriorate further in the UHL_{43} condition (1.0 dB increase in speech recognition threshold, $p > 0.05$), while sound localization was additionally impaired (Error Index increase of 0.33, $p < 0.01$) with an associated large increase in individual variability. Qualitative analyses on a subject-by-subject basis showed that high-frequency audibility was important for speech recognition, while low-frequency audibility was important for horizontal sound localization accuracy. While the data might not be entirely applicable to individuals with long-standing UHL, the results suggest a need for intervention for mild-to-moderate UHL.

1. Introduction

Unilateral hearing loss (UHL) is a relatively common condition. For example, 25% of congenital sensorineural hearing losses affects only one ear (Berninger and Westling, 2011). In school-aged children, 3.0% have sensorineural UHL (Bess et al., 1998). In the United States, the reported prevalence of congenital UHL varies greatly; from 0.35/1000 to 2.7/1000 (Dalzell et al., 2000; Ross et al., 2008; White et al., 1994). In adults (20–69 years old), the prevalence of unilateral and bilateral hearing loss (≥25 dB HL at 0.5, 1, 2, and 4 kHz) is similar (7.9% and 7.8%, respectively), according to the National Health and Nutrition survey in the United States 1999–2004 (n = 5742), meaning that approximately 14 million adult Americans suffer from UHL at important speech frequencies (Agrawal et al., 2008).

UHL may result in inaudible sounds in one ear, effectively disrupting comparison of interaural level and time differences. Subcortical processing of these binaural cues is widely thought to be the foundation for accurate horizontal sound localization and to facilitate the understanding of a target talker in the presence of spatially separate interfering sounds (e.g. Glyde et al., 2013; Grothe et al., 2010; Middlebrooks and Green, 1991). Despite the theoretical risk of deficits in these spatial hearing abilities that are relevant to daily life communication, and the subjective and objective data

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Abbreviations

AOI	Area of Interest
LD-pair	Loudspeaker/display-pair
SNR	Signal-to-Noise Ratio
SRT	Speech Recognition Threshold
UHL	Unilateral Hearing Loss
UHL_{30}	Induced unilateral hearing loss with an average hearing threshold of 30 dB HL across 0.5, 1, 2, and 4 kHz
UHL_{43}	Induced unilateral hearing loss with an average hearing threshold of 43 dB HL across 0.5, 1, 2, and 4 kHz

confirming spatial hearing problems related to UHL (Dwyer et al., 2014; Firszt et al., 2017; Rothpletz et al., 2012; Slattery and Middlebrooks, 1994), spatial hearing is not typically assessed in the clinic. For example, only three studies have assessed the benefit children with UHL received from a conventional hearing aid in a spatial task (Briggs et al., 2011; Johnstone et al., 2010; Updike, 1994). Once UHL is identified, only 21% of children receive a recommendation for amplification within 3 months, as compared to almost 60% of children with minimal bilateral hearing loss (Fitzpatrick et al., 2014).

A possible reason for what seems to be uncertainty in the management of pediatric UHL is the considerable variability in spatial hearing outcomes for adults with UHL (e.g. Firszt et al., 2017; Rothpletz et al., 2012; Slattery and Middlebrooks, 1994). In adults with severe UHL, some of the variability in spatial hearing may be explained by the age at onset of hearing loss, and the hearing thresholds in the ear with near normal hearing (Firszt et al., 2017). The sources of variability in performance for individuals with mild-to-moderate UHL have not to our knowledge been studied. For simulated mild-to-moderate UHL, Corbin et al. (2017) reported that low-frequency audibility (0.5 kHz) was important for spatial release from masking. However, high-frequency audibility might also be important in this context, given the importance of interaural level cues for spatial release from masking (Glyde et al., 2013).

Standard clinical tools for assessment of UHL probably do not capture the difficulties individuals with UHL experience in real life (i.e. spatial hearing tasks are uncommon in the clinic). The approach in the present study was to simulate UHL and study the acute effects on performance in demanding spatial hearing tasks that are relevant to daily communication. Simulated UHL in normal-hearing subjects by plugging one ear using various hearing protectors or monaural head-phone presentation may reveal difficulties associated with decreased audibility in one ear. A number of studies using different approaches with the common goal of "monauralization" in individuals with normal hearing have demonstrated worse sound localization accuracy (e.g. Irving and Moore, 2011; Slattery and Middlebrooks, 1994; Wightman and Kistler, 1997) and worse speech recognition thresholds in spatialized noise (Corbin et al., 2017; Firszt et al., 2017; Persson et al., 2001) than for normal binaural conditions. In those studies, the variability in localization responses was typically largest for stimuli on the side of the plugged ear. However, the audibility of the stimuli has rarely been analyzed in detail. Since previous sound localization results indicate that very low stimulus levels in a plugged ear provide access to binaural cues (Wightman and Kistler, 1997), detailed characterization of the plugged ear hearing thresholds and the associated audibility of the stimuli used is important for understanding how spatial hearing may be affected by UHL of various degrees and configurations. Such knowledge could help in making informed decisions regarding treatment options for individuals with UHL.

The aim here was to study changes in the recognition of speech in multi-source competing speech and sound localization accuracy under ecologically valid conditions, following monaurally induced temporary sound attenuation in normal-hearing adults. A within-subject repeated measures experimental design was used (normal binaural condition, and conditions with two levels of induced UHL). We show, by estimation of hearing sensitivity and an approximation of the speech spectrum (Pavlovic, 1987), that sound localization accuracy and recognition of speech in competing speech are negatively and differentially affected by simulated UHL in a frequency-dependent manner.

2. Materials and methods

2.1. Study design

Two levels of monaural, acute, and temporary sound attenuation were induced in normal-hearing volunteers by an ear plug in the right ear (EAR Classic foam ear plug, 3M, Minneapolis, USA), and a circum-aural hearing protector (Bilsom 847 NST II, Honeywell Safety Products, Rhode Island, USA) placed over the ear plug. The two levels are referred to as "UHL_{30}" (plug) and "UHL_{43}" (plug and hearing protector), based on the average hearing thresholds that were recorded (see the first paragraph in Results). The right ear was chosen as the UHL ear for all the subjects to minimize the number of variables.

Recognition of speech in competing speech and sound localization accuracy were assessed to study the acute effect of induced UHL on binaural sound processing. The speech recognition and sound localization tests were performed sequentially, using one normal binaural condition and two experimental conditions. The order of the conditions was randomized. Retests were performed in the normal condition to quantify the test-retest reliability of the speech recognition and sound localization accuracy measurements.

2.2. Subjects

Eight healthy young adult volunteers (mean (SD) age = 28 (6) years, range = 22–39 years) without any history of noise exposure participated in this study. Pure-tone thresholds, otomicroscopy, tympanometry, and acoustic stapedius reflex measurements were performed immediately before assessment of speech recognition and sound localization. All of the subjects had pure-tone thresholds ≤20 dB HL in both ears at 125, 250, 500, 750, 1000, 1500, 2000, 3000, 4000, 6000, and 8000 Hz, as measured via insert earphones (Ear Tone ABR; Etymotic Research Inc., IL) using a fixed-frequency Békésy technique (Berninger et al., 2014), which is characterized by high reliability (e.g. Berninger and Gustafsson, 2000; Paintaud et al., 1994). The subjects received oral and written information about the study before enrollment. Written informed consent was obtained for all subjects, and the study was approved by the regional ethical committee in Stockholm, Sweden.

2.3. Quantification of simulated unilateral hearing loss

The effect of the sound attenuation devices on hearing sensitivity was quantified by measuring frequency-modulated tone thresholds in sound field without ear plugs (normal condition), with bilateral ear plugs, and with bilateral ear plugs and hearing protectors (see ISO-4869-1, 1990). The measurements were