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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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ABSTRACT

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 performed in a double-walled sound booth (4.0 m × 2.6 m × 2.1 m), allowing threshold determination down to −10 dB HL (mean ambient sound level = 20 dB (A) obtained during 15 s measurement; reverberation time $T_{30} = 0.09$ s at 500 Hz, as recorded with a B&K 2238 Mediator and a B&K 2260 Investigator (Brüel & Kjær, Nærum, Denmark)). Subjects were seated in the center of the room, 1.8 m from a loudspeaker at 0° azimuth. Thresholds were recorded immediately prior to the speech recognition and sound localization accuracy experiments (during which the sound attenuation devices in the left ears were removed, see below).

The pulsing frequency-modulated tones had center frequencies of 500, 1000, 2000, 3000, 4000, and 6000 Hz (±12.5% frequency deviation, 20 Hz modulation frequency, pulse duration = 400 ms, 50% duty cycle). The thresholds were recorded with a computerized Békésy-technique (level variation ≈1 dB/s, see Berninger et al., 2014), always starting at 30 dB HL (ISO-389-7, 1996, minimum audible field). The threshold was computed as the mean (in dB) of three turning-point pairs, neglecting the first pair.

2.4. Recognition of speech in spatially separate competing speech

2.4.1. Setup

Recognition of speech in competing speech was measured in sound field in the same room as used for the measurement thresholds. Subjects were seated in the center of the room, 1.8 m from a loudspeaker at 0° azimuth, from which the target signal was presented. Four loudspeakers, presenting competing speech signals, were placed in the corners of the room, corresponding to ±30° azimuth (frontal horizontal plane) and ±150° azimuth (in the rear horizontal plane), thus surrounding the subject (Berninger and Karlsson, 1999).

2.4.2. Stimulus and interferers

The target speech (female voice) was the Hagerman sentences (Hagerman, 1982). Each sentence consisted of five grammatically correct words with low semantic predictability in a fixed syntax (e.g. “Jonas gav elva röda skålar”, in translation: “Jonas gave eleven red bowls”). Twelve lists (and one training list), each containing ten sentences, were used. The interferers comprised four non-correlated recordings of a single male talker reading a novel. The interferers were presented at a fixed overall level of 63 dB SPL Ceq (12 min recording time), as measured at the position of the subjects' head (Berninger and Karlsson, 1999). Speech interferers were chosen to resemble a demanding everyday listening condition.

2.4.3. Procedure

Subjects were instructed to face the frontal loudspeaker during the entire test and were informed that the target speech originated from that loudspeaker. They were asked to repeat the words of one training list (always the same list) and two target lists, and their oral responses were recorded by an experimenter outside the test room. The experimenter listened to the target signal and the subject's responses through a feed-back system and scored the responses after each sentence. Guessing was encouraged and no feedback was provided. Words had to be repeated grammatically correctly to be scored as correct. The training started at a signal-to-noise ratio (SNR) of +10 dB. For the following training sentences, the target speech level decreased up to three times in 5 dB steps, then up to three times in 3 dB steps, and then in 2 dB steps until the number of correct words was ≤2. Following training, the scheme for level adjustment of the target speech was +2 dB for zero correctly identified words, +1 dB for one correctly identified word, 0 dB for two correctly identified words, −1 dB for three correctly identified words, −2 dB for four correctly identified words, and −3 dB for five correctly identified words, aiming at a threshold of 40% words correct. That threshold and the adaptive scheme for level adjustment were chosen based on computer simulations and analysis of the maximum steepness of the psychometric function (Hagerman, 1979, 1982; Hagerman and Kinnefors, 1995). The speech recognition threshold (SRT) was defined as the mean of the SNRs for the last ten presented sentences (Hagerman and Kinnefors, 1995; Plomp and Mimpen, 1979).

2.5. Sound localization accuracy

The setup, stimulus and procedure used for sound localization measurements are described in Asp et al. (2016). Sound localization responses were objectively obtained using an eye-tracking system, using a rapid (≈3 min) procedure with high reliability (Asp et al., 2016).

2.5.1. Setup

Sound localization accuracy was measured in quasi-free sound field in a double-walled sound booth (4.1 m × 3.3 m x 2.1 m) with low ambient sound level (25 dB (A)), and short reverberation time ($T_{30} = 0.11$ s at 500 Hz), as recorded with a B&K 2238 Mediator and a B&K 2260 Investigator (Brüel & Kjær, Nærum, Denmark), respectively. Subjects were seated facing twelve active loudspeakers (ARGON 7340A, Argon Audio, Sweden) placed equidistantly in a 110-degree arc in the frontal horizontal plane, resulting in loudspeaker positions at ±55, ±45, ±35, ±25, ±15, and ±5°. Seven-inch video displays were mounted below each loudspeaker, resulting in twelve loudspeaker/display pairs (LD pairs). The loudspeakers and the loudspeaker stands were covered in black cloth, so that only the video displays were visible. The approximate distance from the head of the subject to the loudspeakers and the video displays was 1.2 m and 1.1 m, respectively. The loudspeakers were at approximate ear level, and were vertically adjusted along with the video displays to accommodate different heights of the subjects.

An eye tracking system (Smart Eye Pro, Smart Eye AB, Gothenburg, Sweden) was used to record the gaze of the subjects in relation to the LD pairs (see Asp et al., 2016 for details). The coordinates of the video displays and loudspeakers were defined in three dimensions in the eye-tracking system, resulting in Areas of Interest (AOI) (Asp et al., 2016; Gredebäck et al., 2010). In total, twelve AOIs, each with width 0.17 m and height 0.55 m, constituted a continuous array of AOIs in a 3D model, corresponding to the physical LD pairs.

2.5.2. Stimulus

An ongoing auditory-visual stimulus (a colorful cartoon movie playing a continuous melody) was presented. The audio stimulus had a level of 63 dB SPL (A) and long-term frequency spectrum similar to the unmodulated noise used with the Hagerman Sentences, and thus similar to the spectrum of a female voice (Hagerman, 1982). Beyond the natural amplitude fluctuations in the signal, no roving of the sound level was applied.

2.5.3. Procedure

Immediately prior to each test session, a calibration of the subjects' gaze relative to the LD pairs was performed (Asp et al., 2016).

The stimulus was initially presented from the LD-pair at −5°, just to the left of frontal incidence. After an average time interval of 7 s, the visual stimulus was stopped and the sound was instantaneously shifted to a randomized loudspeaker. The visual stimulus was reintroduced after a sound-only period of 1.6 s to allow sustained acquisition of gaze towards the video-screens. During the 1.6 s sound-only period, the subjects were guided by audition only as to where the active sound source was located. The subjects were instructed to follow the auditory-visual stimulus and that sound-only periods would occur, and were informed that they were allowed to move their heads freely. The auditory and visual shifts were repeated 24 times according to a pre-generated list of randomized shifts with the constraint that no LD pair was used a second time before each of the twelve LD pairs had been used.

Subjects' pupil positions relative to the LD pairs were sampled at 20 Hz. The resulting gaze/AOI intersections were derived from the output of the eye tracker and stored as a function of time. The perceived auditory azimuth was defined as the median of the final 10 gaze/AOI intersection samples obtained during the 1.6 s sound-only period, i.e. a 500 ms sampling period. Sound localization accuracy was quantified by an Error Index (e.g. Asp et al., 2011; Gardner and Gardner, 1973) which was calculated as:

$$EI = \frac{\sum\limits_{(i,\ k) \in P} |i - k|}{\left(\sum\limits_{i \in P} \sum\limits_{k=1}^{n} |i - k| \right) \Big/ \mathrm{n}} \tag{1}$$

where P is the set of loudspeakers (1–12), i = the presented loudspeaker (1–12), k = the perceived loudspeaker (1–12), and n = 12 (the number of loudspeakers). The Error Index ranged from 0 (perfect performance) to 1 (random performance). The data from the sound localization test were also analyzed as perceived versus presented sound-source azimuth.

2.6. Analyses

Repeated measures ANOVAs were used to study the effect of listening condition (normal, UHL_{30}, UHL_{43}) on the SRT and Error Index. Post-hoc comparisons between conditions were performed using Student's t-tests for dependent samples. For sound localization accuracy, median perceived sound-source azimuths versus presented sound-source azimuths were calculated across the entire spatial range tested.

3. Results

3.1. Simulated unilateral hearing loss

The mean frequency-modulated tone thresholds (across 0.5, 1, 2, and 4 kHz) was 3.4 dB HL in the normal condition and 30.2 dB HL and 43.3 dB HL in the UHL_{30} and UHL_{43} conditions, respectively. The induced hearing loss in the UHL_{30} condition was larger at high than low frequencies (Fig. 1). The mean frequency-modulated tone thresholds varied from 23.6 dB HL at 1 kHz to 40.4 dB HL at 3 kHz. The corresponding standard deviations varied from 5.3 to 7.6 dB.

The induced hearing loss in the UHL_{43} condition was also larger at high than low frequencies. The mean thresholds varied from 37.7 dB HL at 1 kHz to 50.7 dB HL at 4 kHz (Fig. 1). However, the additive effect of the circum-aural hearing protector was larger at low than high frequencies. As an example, the mean threshold difference between conditions UHL_{30} and UHL_{43} was 14.1 dB at 1 kHz and 9.8 dB at 3 kHz (Fig. 1).

The individual variability in thresholds was quite high in both experimental conditions (see supplementary material online). For example, in the UHL_{30} condition, the threshold ranges at 0.5 and 3 kHz were 10.0 and 21.6 dB, respectively. The corresponding ranges in the UHL_{43} condition were 15.6 and 25.6 dB, respectively.

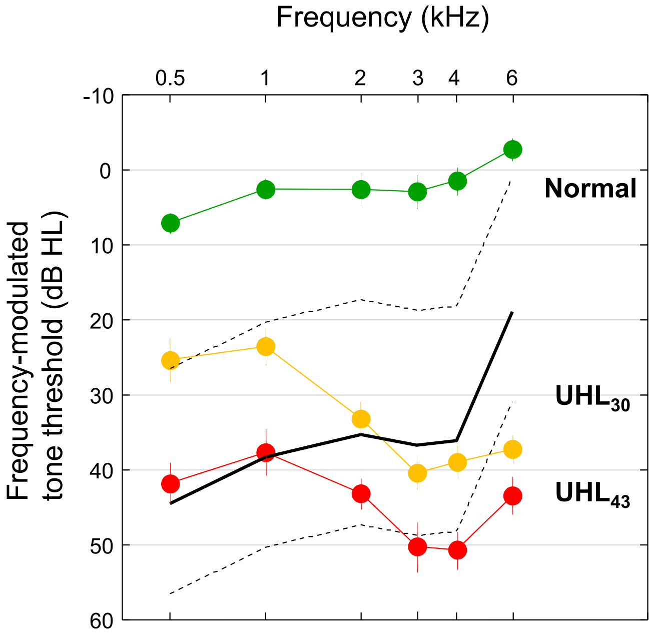

Fig. 1. Mean thresholds for detecting frequency-modulated tones (n = 8 subjects) in sound field in normal (green) and in temporary induced unilateral hearing loss conditions (UHL_{30}; yellow and UHL_{43}; red). Error bars denote ±1 standard error of the mean. The solid black line is derived from Pavlovic (1987) and illustrates the hearing level of speech (in 1/3 octave bands) in dB HL at an overall level of 63 dB SPL. The minimum (−18 dB) and maximum (+12 dB) of the speech spectrum are depicted by dashed lines.

3.2. Recognition of speech in spatially separate competing speech

There was a significant effect of listening condition ($F(2, 14) = 8.6$, $p < 0.01$). The mean (SD) SRT in the normal condition was −15.1 dB (1.6 dB). Post-hoc paired comparisons showed significant increases in SRT for the UHL_{30} (2.0 dB increase, $p = 0.008$) and the UHL_{43} (3.0 dB increase, $p = 0.004$) conditions, respectively (Fig. 2, upper panel; Table 1).

There was no significant difference in SRT between UHL_{30} and UHL_{43} ($t = -1.11$, $p = 0.30$, $n = 8$).

All the subjects had a lower SRT in the normal than in the UHL_{30} and UHL_{43} conditions, except subject 7 who showed a slightly lower SRT (by 0.7 dB) in condition UHL_{30} than in the normal condition (Table 1). The range of individual SRTs (Table 1) was 5.4 dB in the normal condition, 4.4 dB in the UHL_{30} condition, and 3.9 dB in the UHL_{43} condition, reflecting quite similar individual variability in the different listening conditions.

3.2.1. Reliability

The mean (SD) test–retest difference for the SRT was 0.30 dB (1.81). The 95% confidence interval [-1.22, 1.82] included 0, that is, there was no significant learning effect. Based on the test-retest data, the 95% confidence interval for a single speech recognition measurement was estimated to be ±2.5 dB ($(SD(test - retest)/\sqrt{2}) \times 1.96$).

3.3. Sound localization accuracy

There was a significant effect of listening condition ($F(2, 14) = 22.4$, $p < 0.0001$). Post-hoc tests showed that sound localization accuracy was significantly better in the normal than the UHL_{30} (mean Error Index = 0.21, $p < 0.0001$) and the UHL_{43} (mean Error Index = 0.54, $p < 0.001$) conditions. Sound localization

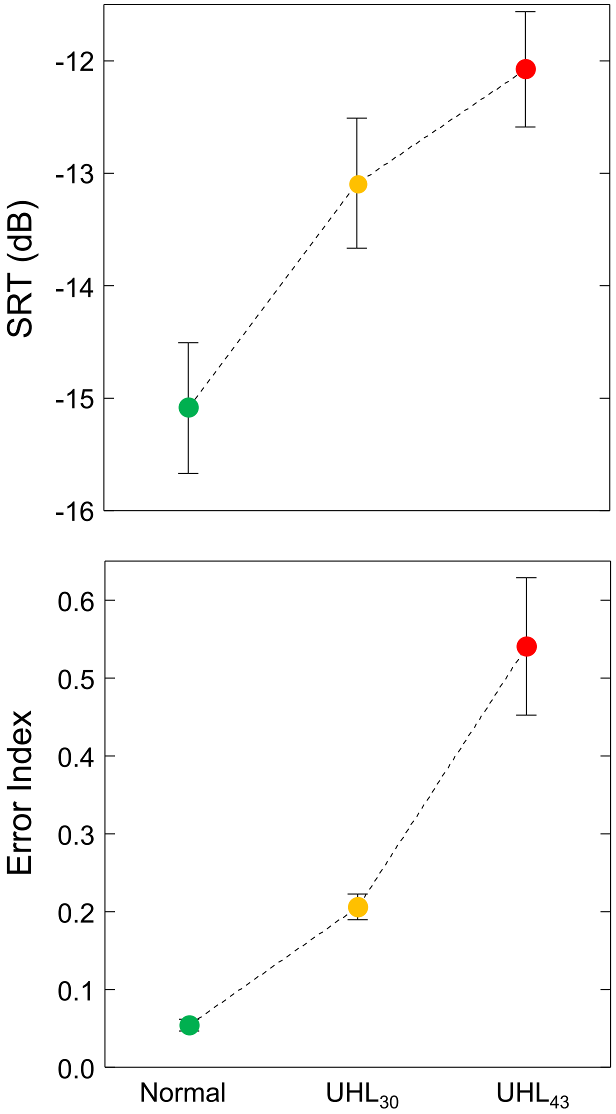

Fig. 2. Mean recognition threshold (SRT) for speech in spatially separate competing speech (upper panel) and horizontal sound localization accuracy (lower panel) for the normal listening condition (green) and for conditions UHL$_{30}$ (yellow) and UHL$_{43}$ (red). Error bars denote ±1 standard deviation.

accuracy was significantly better in the UHL$_{30}$ than the UHL$_{43}$ condition ($p = 0.008$).

As originally published in Asp et al. (2016), the subjects achieved Error Index values close to 0 in the normal condition (mean (SD) = 0.054 (0.021), demonstrating near perfect sound localization accuracy (see individual Error Indices in Table 1 and group data in Fig. 2, lower panel). For all the subjects, the Error Index increased in both the UHL$_{30}$ and UHL$_{43}$ conditions, with the most pronounced effect in the latter for 5 of 8 subjects (Table 1). The Error Index range was quite low in the normal condition (0.08) and in the UHL$_{30}$ condition (0.13), while it was considerably larger in the UHL$_{43}$ condition (0.64) (Table 1).

3.3.1. *Reliability*

The reliability analysis was originally published in Asp et al. (2016) and is included here to facilitate interpretation of the results. In the normal condition, the mean (SD) sound localization accuracy test–retest difference was 0.013 (0.039) ($n = 8$). The 95% confidence interval [-0.020, 0.046] included 0, that is, there was no significant learning effect. Based on the test-retest data, the 95% confidence interval for a single sound localization accuracy measurement was estimated to be ±0.054 $((SD(test-retest)/\sqrt{2}) \times 1.96)$.

3.4. *Perceived versus presented azimuth*

The effect of the acute UHL was qualitatively analyzed by plotting the median (Fig. 3) and individual (Fig. 4) perceived versus presented sound-source azimuth for each listening condition.

3.4.1. *Normal condition*

In the normal condition, the median perceived azimuths coincided with the presented sound-source azimuths across the entire spatial range, except at +15° where a lateral offset of 5° was found (Fig. 3, top panel). The inter-quartile range (25–75%) of perceived azimuth in relation to presented azimuth was zero for 9 out of 12 sources, and within 10° for the remaining 3 sources, reflecting low intersubject variability. Each of the eight subjects typically localized the presented azimuths across the entire spatial range (Fig. 4, panels in left column).

3.4.2. *Experimental conditions*

In the UHL$_{30}$ condition, the median perceived azimuths in the right hemisphere (plugged side) coincided with the presented sound-source azimuths except at the most lateral azimuth (+55°) (Fig. 3, middle panel), where the median offset was 10°. Medians in the left hemisphere were either biased by $\leq$ 10° toward the left (open) ear (at the presented sound-source azimuths of −5, - 15, -25, and −45°), or showed a 1:1 relationship with the presented sound-source azimuth (−35 and −55°). Individual variability in the

Table 1
Individual recognition thresholds for speech in competing speech and sound localization accuracy for the eight bilaterally normal-hearing subjects under normal and experimental (UHL$_{30}$ and UHL$_{43}$) conditions. Retest data are provided for the normal condition.

Id	Speech recognition threshold (dB)				Error Index			
	Normal	Normal (retest)	UHL$_{30}$	UHL$_{43}$	Normal	Normal (retest)	UHL$_{30}$	UHL$_{43}$
1	−11.6	−14.5	−11.2	−11.1	0.03	0.05	0.25	0.71
2	−15.5	−15.4	−11.2	−13.8	0.08	0.04	0.23	0.78
3	−17.0	−14.3	−14.8	−12.5	0.07	0.01	0.28	0.26
4	−15.0	−16.4	−13.2	−14.0	0.03	0.09	0.16	0.20
5	−14.5	−15.8	−11.7	−12.3	0.04	0.00	0.16	0.84
6	−15.6	−16.0	−13.3	−12.4	0.08	0.07	0.21	0.31
7	−14.9	−15.9	−15.6	−10.1	0.04	0.03	0.22	0.64
8	−16.6	−14.8	−13.7	−10.4	0.06	0.04	0.15	0.59
Mean	**−15.1**	**−15.4**	**−13.1**	**−12.1**	**0.05**	**0.04**	**0.21**	**0.54**
SD	1.6	0.8	1.6	1.4	0.02	0.03	0.05	0.25

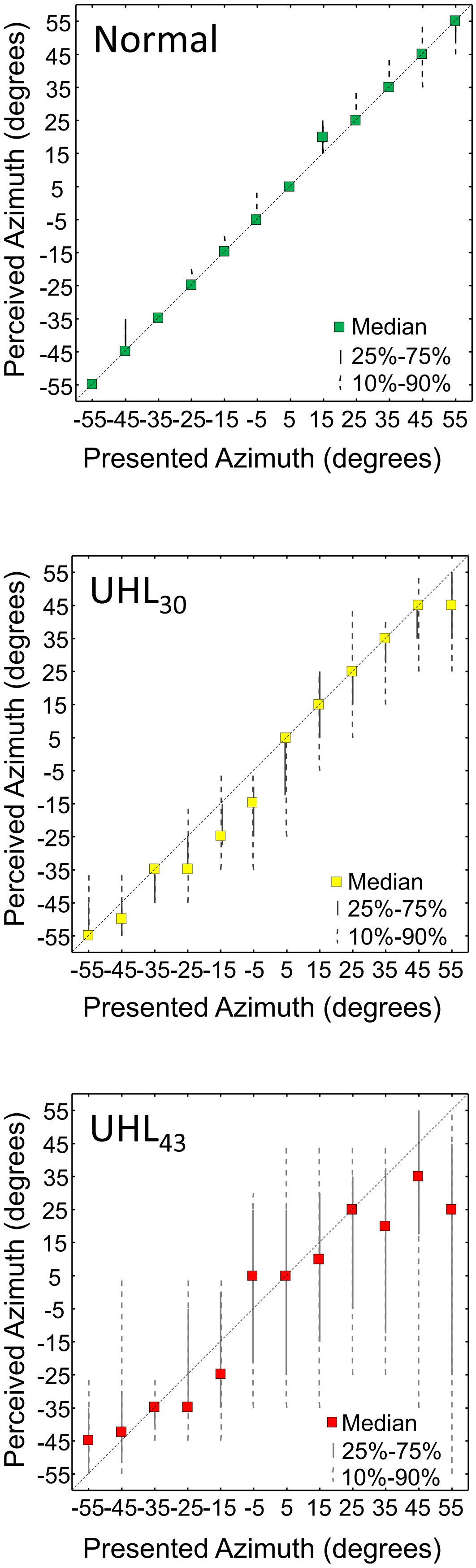

Fig. 3. Symbols show the median perceived sound-source azimuths vs. presented azimuths for normal (green, top panel) and UHL conditions (UHL$_{30}$; yellow, middle panel and UHL$_{43}$; red, bottom panel). Solid and dashed vertical error bars denote quartiles (25%–75%) and percentiles (10%–90%), respectively. Symbols on the diagonal dashed lines indicate a perfect match between perceived and presented azimuth. Symbols far from the diagonal lines reflect poor sound localization accuracy.

UHL$_{30}$ condition was higher than in the normal condition, with interquartile ranges between 10 and 20°. Individually perceived azimuths corresponded fairly well with the presented azimuths (Fig. 4, panels in middle column). However, relatively large maximum errors of 20–30° occurred for all the 8 subjects, and such errors ($\geq 20°$, $n = 15$ errors) were biased towards the left (open) ear in 80% of cases.

In the UHL$_{43}$ condition, an offset of the median perceived azimuths in relation to presented sound-sources occurred for 4 of 6 azimuths in both the left and right hemispheres (Fig. 3, bottom panel). The median offset ranged between 0 and 30°, with the largest median offset (30°) at the right-most source location (on the side of plugged ear).

Large individual angular errors occurred. All the subjects showed at least one perceived azimuth that was 30° off target (Fig. 4, panels in right column). Subjects 3 and 4 showed the smallest errors overall (mostly errors of 10°), which was reflected in their Error Indices being lower than for the other subjects (Table 1). Interquartile ranges, reflecting individual differences across azimuths, were 5–70° and on average were approximately twice as large on the side of the plugged ear (mean interquartile range = 49°) as on the side of the open ear (mean interquartile range = 26°). A linear regression analysis of the interquartile ranges as a function of azimuth demonstrated progressively larger inter-individual variability toward the side of the plugged ear (interquartile range = 37.3 + 0.39 × Presented Azimuth (degrees), $r = 0.82$, $p < 0.01$).

3.5. Unilaterally elevated hearing thresholds have different effects on speech recognition threshold in competing speech and sound localization accuracy

The earplug and hearing protector in combination (UHL$_{43}$) distinctly increased the mean Error Index ($p < 0.01$) relative to the UHL$_{30}$ condition (mean = 0.33 increase in Error Index), whereas the mean increase in SRT (1.0 dB) did not reach statistical significance ($p > 0.05$).

Given the significance of mid-to-high frequency information for speech recognition in noise (Hagerman, 1984; Smoorenburg et al., 1982), and the dominant role of low-frequency information for horizontal sound localization (Wightman and Kistler, 1992), we assessed whether audibility as a function of frequency in the plugged ear could explain the differential effects on sound localization accuracy and recognition of speech in competing speech. Post-hoc analyses of the tone thresholds in the plugged ear in relation to the function describing hearing level of speech (Pavlovic, 1987, Table 5) were performed (see individual thresholds plotted together with importance functions in supplemental content online). At least three of the four high-frequency thresholds (2, 3, 4 and 6 kHz) in the plugged ear were above or at the average hearing level of speech for six of the eight subjects in the UHL$_{30}$ condition (subjects 1, 2, 3, 4, 6, 8) (cf. Supplementary Material online, figures illustrating individual thresholds), which likely resulted in significantly reduced audibility of high-frequency information in the plugged ear. The added threshold shift in condition UHL$_{43}$ further affected high-frequency audibility, but a major part of the high frequency energy in the speech signal was already inaudible.

In contrast, the mean low-frequency thresholds (0.5 and 1 kHz)

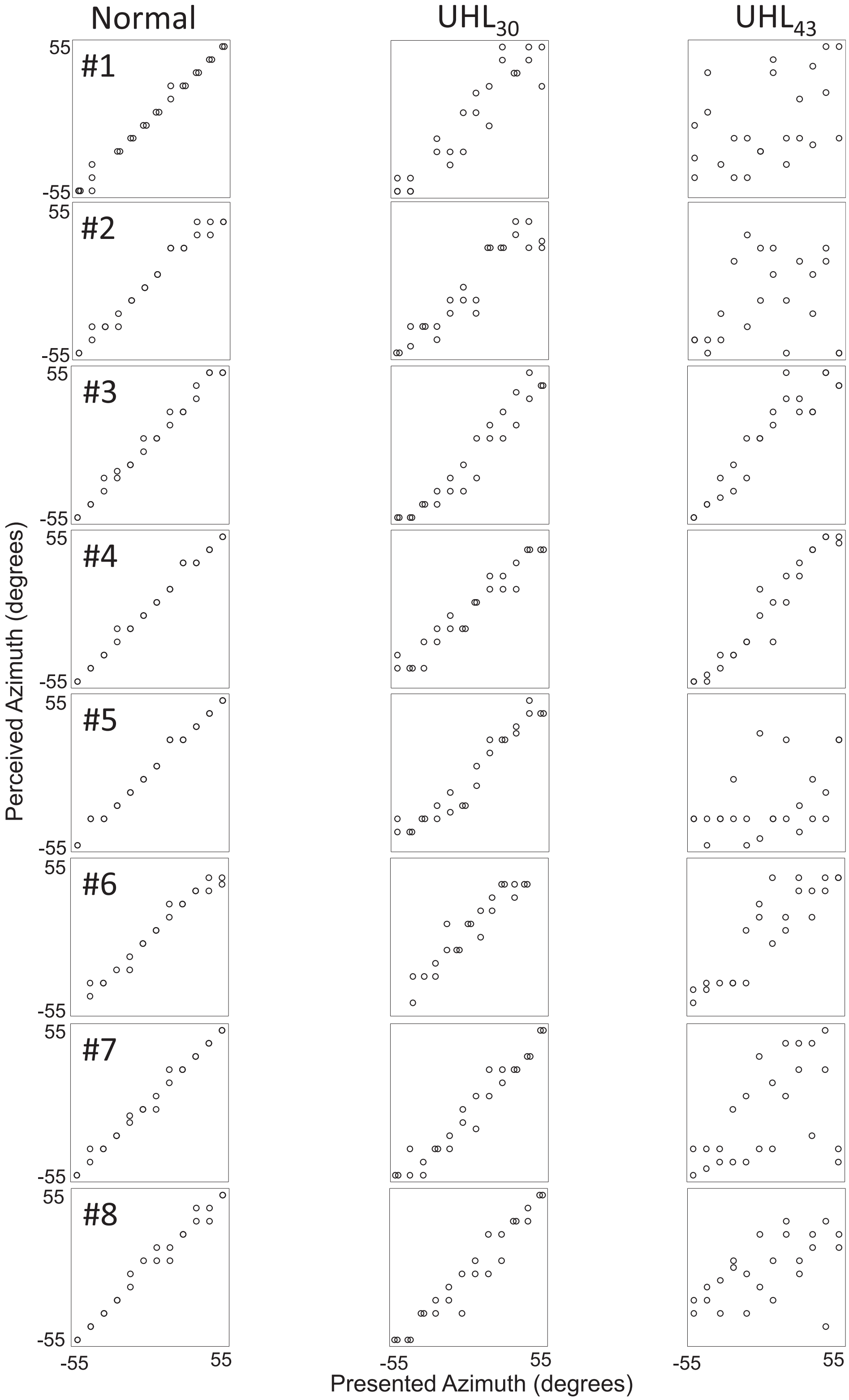

Fig. 4. Individual horizontal sound localization. Open circles show perceived sound-source azimuth vs. presented sound-source azimuth. The left, middle, and right columns show results for normal and UHL conditions (UHL$_{30}$ and UHL$_{43}$).

indicated that the low-frequency energy of the localization stimuli was clearly audible in the UHL$_{30}$ condition, whereas it was not (on average) in the UHL$_{43}$ condition (Fig. 1). Visual inspection of individual UHL$_{43}$ thresholds overlaid on average speech levels and dynamic range (Pavlovic, 1987) suggested that low-frequency information in the sound localization stimulus was audible (thresholds below the average speech level) for the two subjects showing the lowest Error Index (subjects 3 and 4) and for the two subjects with Error Index closest to the median Error Index (subjects 8 and 7). Low-frequency information was less audible (thresholds in general above the average speech level) for the two subjects with the highest Error Index (subjects 5 and 2) and for the remaining subjects who showed high (subject 1) and low (subject 6) Error Index.

4. Discussion

This study aimed at characterizing spatial hearing deficits resulting from experimentally induced UHL in conditions representing everyday life. The two levels of simulated UHL revealed different and frequency-dependent effects on horizontal sound localization accuracy and recognition of speech in spatially separate competing speech. The results showed that a “mild” induced artificial UHL (30 dB HL) increased the SRT in spatially separate competing speech (2.0 dB, $p = 0.008$), whereas a “moderate” induced UHL (43 dB HL) produced only a small and non-significant extra effect (1.0 dB, $p = 0.30$). Moreover, sound localization accuracy was clearly affected by the induced UHLs, but, in contrast to speech recognition, more so in the UHL_{43} condition, in which individual variability was much larger than in the normal and UHL_{30} conditions. Qualitative analyses on a subject-by-subject basis indicated that high-frequency audibility (in the experimental ear) was important for speech recognition, while low-frequency audibility was more important for horizontal sound localization accuracy.

4.1. *Individual variability in sound localization accuracy*

There were large intersubject differences in sound localization accuracy in the UHL_{43} condition (Error Index-range: 0.20–0.84). Estimates of the audibility of the localization stimulus for each subject in the UHL_{43} condition indicated that sound localization accuracy was related to subjects' access to low-frequency sound, consistent with the dominant role of low-frequency interaural time differences in sound localization (Wightman and Kistler, 1992). However, the relation between sound localization accuracy and the audibility of low-frequency sound was not 1:1. Subject 7 showed poor sound localization accuracy despite audible low-frequency information (relative to the average speech level in Pavlovic, 1987) and subject 6 showed good sound localization accuracy despite largely inaudible low-frequency information.

If localization were determined solely by the interaural time difference, then as a result of the interaural time difference produced by the EAR earplug (estimated to ~150 μs in Kumpik et al., 2010) the Error Index would have been markedly higher than observed. Assuming the radius of a human head to be 8.75 cm and the speed of sound in room-temperature air to be 344 m/sec, that estimated interaural time difference corresponds to a shift in azimuth of ~18°, which is more than twice as large as the average of the individual mean angular errors found in the UHL_{30} condition (7.9°, data not shown). It thus seems likely that the subjects at least partly attended to interaural level differences and/or spectral cues or monaural level cues when the low-frequency information was inaudible or if the interaural time difference was perturbed. The subjects might also have adapted to the interaural time difference shift.

4.2. *Comparison with previous studies*

To our knowledge, the present study is the first to characterize spatial hearing deficits for two different levels of simulated UHL within the same subjects. However, a number of previous studies simulated a single level of UHL, with the goal of assessing deficits in sound localization and speech recognition (Corbin et al., 2017; Firszt et al., 2017; Irving and Moore, 2011; Persson et al., 2001; Rothpletz et al., 2012; Slattery and Middlebrooks, 1994; Wightman and Kistler, 1997). A recent study (Firszt et al., 2017) reported data from subjects with simulated UHL using competing speech as a masker, similar to the current study and to real-life circumstances. The distinct shifts in SRT and in the Error Index in the present study are consistent with the differences between a group of NH subjects ($n = 23$), and a group of NH subjects with a simulated UHL ($n = 25$) (Firszt et al., 2017). In that study, the magnitude of the monaural attenuation was not assessed pyschoacoustically (attenuation was achieved either with an ear plug or with a combination of an ear plug and a circum-aural hearing protector). There was a significant SRT difference of 2–3 dB (as estimated from Fig. 1 in Firszt et al., 2017) between the two groups, as obtained in a diffuse “restaurant noise” presented from 8 loudspeakers arranged in a 360-degree array in the horizontal plane. That difference was similar to the difference found in the present study (2.0 dB and 3.0 dB differences in the UHL_{30} and UHL_{43} conditions, respectively). Similarly, for horizontal sound localization accuracy, overall performance was distinctly worse for the group with simulated UHL than for the NH group in the Firszt et al. study (2017), as indicated by a mean RMS error of nearly 40° versus RMS errors close to zero for the NH group (estimated from Fig. 3 in Firszt et al., 2017). Since the present study quantified sound localization accuracy using the Error Index, direct comparison of sound localization accuracy is difficult. However, the large RMS difference in Firszt et al. (2017) appears consistent with data obtained in the UHL_{43} condition here. Furthermore, the larger localization errors and response variability on the side of the simulated UHL versus the unplugged side reported here also occurred in the data of Firszt et al. (2017), and others (Kumpik et al., 2010; Slattery and Middlebrooks, 1994).

4.3. *Study limitations*

While the most important cues for horizontal sound localization are interaural differences in time and level (e.g. Middlebrooks and Green, 1991; Oldfield and Parker, 1986; Wightman and Kistler, 1992), the individual filtering characteristics of the pinna result in cues for horizontal localization of broad band sounds (Butler, 1986; Musicant and Butler, 1984). Consequently, besides higher attenuation in the UHL_{43} than the UHL_{30} condition, the covered right pinna might have affected sound localization accuracy.

We also note that there may be differences between transient changes in hearing sensitivity in one ear and long-standing UHL, as indicated by improvements in localization of broad band sounds with a flat spectrum following training with one ear plugged (King et al., 2000; Kumpik et al., 2010).

Although unlikely, either ear plug may not have been inserted as well as the contralateral ear plug so the attenuation values might not be strictly correct.

4.4. *Clinical implications and future research*

Individuals with UHL report difficulties in spatial hearing (Noble and Gatehouse, 2004). Despite these subjective reports, an estimated prevalence of sensorineural UHL of 3.0% in school-aged children (Bess et al., 1998) which increases to 7.9% in adulthood (Agrawal et al., 2008), and the associated risk of having to repeat at least one year in school (up to 10 times more common than in normal-hearing children) (Bess and Tharpe, 1986; Bovo et al., 1988; Hartvig Jensen et al., 1989) and poor language comprehension (Lieu et al., 2010, 2012), surprisingly little is known about interventional outcomes. The present study suggests a need for intervention for mild-to-moderate UHL, on the basis of clearly and negatively affected sound localization accuracy and speech recognition, in situations resembling daily circumstances. However, the experimental data might not be entirely applicable to individuals with UHL and their associated experience with an asymmetry. As an example, long-standing severe unilateral sensorineural hearing loss (Slattery and Middlebrooks, 1994) or acquired unilateral conductive hearing loss (Agterberg et al., 2012) is not always associated with deficits in horizontal sound localization. Clinical research is needed using large groups of subjects with various UHL profiles, to assess deficits and the effectiveness of, for example, hearing aid interventions.

Conflicts of interest

None.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heares.2017.11.008.

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