Effect of Tinnitus and Duration of Deafness on Sound Localization and Speech Recognition in Noise in Patients With Single-Sided Deafness

Yang-Wenyi Liu[1,2], Xiaoting Cheng[1,2], Bing Chen[1,2] (iD),
Kevin Peng[3,4], Akira Ishiyama[4], and Qian-Jie Fu[4] (iD)

Abstract

Patients with single-sided deafness (SSD) often experience poor sound localization, reduced speech understanding in noise, reduced quality of life, and tinnitus. The present study aims to evaluate effects of tinnitus and duration of deafness on sound localization and speech recognition in noise by SSD subjects. Sound localization and speech recognition in noise were measured in 26 SSD and 10 normal-hearing (NH) subjects. Speech was always presented directly in front of the listener. Noise was presented to the deaf ear, in front of the listener, or to the better hearing ear. Tinnitus severity was measured using visual analog scale and Tinnitus Handicap Inventory. Relative to NH subjects, SSD subjects had significant deficits in sound localization and speech recognition in all listening conditions ($p < .001$). For SSD subjects, speech recognition in noise was correlated with mean hearing thresholds in the better hearing ear ($p < .001$) but not in the deaf ear. SSD subjects with tinnitus performed poorer in sound localization and speech recognition in noise than those without tinnitus. Shorter duration of deafness was associated with greater tinnitus and sound localization difficulty. Tinnitus visual analog scale and Tinnitus Handicap Inventory were highly correlated; the degree of tinnitus was negatively correlated with sound localization and speech recognition in noise. Those experiencing noticeable tinnitus may benefit more from cochlear implantation than those without; subjective tinnitus reduction may be correlated with improved sound localization and speech recognition in noise. Subjects with longer duration of deafness demonstrated better sound localization, suggesting long-term compensation for loss of binaural cues.

Keywords

Introduction

In normal-hearing (NH) individuals, stimulation patterns across ears are fused, sound subjectively similar, and provide similar intelligibility. With both ears, NH listeners experience better sound localization and can use spatial cues to better understand speech in noise, particularly when speech and noise are spatially separated. In patients with asymmetric hearing loss, binaural cues are distorted due to the difference in stimulation patterns between ears. The most extreme variant of asymmetric hearing loss is single-sided deafness (SSD), in which patients have NH in one ear and a severe to profound hearing loss in the contralateral ear. In SSD patients,

[1]Department of Otology and Skull Base Surgery, Eye Ear Nose and Throat Hospital, Fudan University, Shanghai, China
[2]NHC Key Laboratory of Hearing Medicine, Fudan University, Shanghai, China
[3]House Clinic, Los Angeles, CA, USA
[4]Department of Head and Neck Surgery, David Geffen School of Medicine, University of California, Los Angeles, CA, USA

The first two authors are cofirst authors.

Corresponding authors:
Qian-Jie Fu, Department of Head and Neck Surgery, David Geffen School of Medicine, University of California, Los Angeles, CA, USA.
Email: qfu@mednet.ucla.edu
Bing Chen, Department of Otology and Skull Base Surgery, Fudan University, Shanghai, China.
Email: bingchen@fudan.edu.cn

binaural cues used for sound localization and spatial speech recognition in noise, including interaural differences in latency and intensity, are lost (Arndt et al., 2011; Buechner et al., 2010; Chan, Freed, Vermiglio, & Soli, 2008; Jacob, Stelzig, Nopp, & Schleich, 2011; Vermeire & Van de Heyning, 2009). SSD has been associated with derangements in functional synaptogenesis in development (Kral, Hubka, Heid, & Tillein, 2013). In children, SSD has been associated with increased rates of grade failures, behavioral issues, and lower intelligence quotient (Culbertson & Gilbert, 1986; Lieu, 2004). In adults, SSD is associated with significantly worse speech understanding in both noise and quiet, worse sound localization, and increased listening effort (Dwyer, Firszt, & Reeder, 2014).

A significant portion of SSD patients (54%–84%) may have debilitating tinnitus in the deaf ear (Quaranta, Bartoli, & Quaranta, 2004; Wie, Pripp, & Tvete, 2010). Debilitating tinnitus is often reported to affect daily quality of life negatively (Tyler & Baker, 1983), and tinnitus may result in emotional distress, clinical depression, and communication problems (Jakes, Hallam, Chambers, & Hinchcliffe, 1985). Tinnitus is often accompanied by hearing loss (Kim et al., 2011) but may even play a significant role in auditory perception irrespective of hearing loss. This is because tinnitus may result from deafferentiation of peripheral input to the central auditory system, which may or may not be reflected by a measurable change in auditory thresholds (Diges, Simon, & Cobo, 2017). Mertens, Kleine Punte, De Ridder, and Van de Heyning (2013) evaluated the association between tinnitus severity in the deaf ear and speech recognition in noise in the NH (nontinnitus) ear by turning on or off the external cochlear implant (CI) processor in SSD patients with CI. They found that after turning on the external CI processor in the deaf ear, tinnitus loudness was reduced, even though there was no acoustic input to the CI processor. Speech recognition in noise in the NH ear was also improved when the external CI processor in the deaf ear was turned on. These data suggest that speech recognition in noise may be associated with severity of tinnitus in SSD patients.

However, unilateral tinnitus severity following sudden sensorineural hearing loss likely decreases over time in a subset of patients even if left untreated (Muhlmeier, Baguley, Cox, Suckfull, & Meyer, 2016). This is related to the observation that the loss of unilateral peripheral input in SSD is associated with spatial reorganization of the auditory cortex in both hemispheres over time (Chang et al., 2016). Hearing optimization in the only hearing ear in SSD patients may require remediation of these central auditory changes. While SSD patients generally have difficulty with sound-source localization (i.e., Wie et al., 2010), Yu et al. (2018) reported that sound-source localization with one hearing ear may be improved by active training.

The interplay between tinnitus, hearing loss, and auditory perception is complex, and this interplay may be further complicated by the duration of deafness. It has been shown that unilateral tinnitus severity following sudden sensorineural hearing loss likely decreases over time in some SSD patients (Muhlmeier et al., 2016), and SSD patients may adapt to the loss of binaural cues over time via the remediation of both spatial and temporal central auditory processing (Chang et al., 2016). The present study aims to evaluate the association or effect of tinnitus and duration of deafness on sound localization and speech recognition in noise with and without spatial cues in a cohort of SSD subjects. Because tinnitus may represent a deafferentiation of peripheral input, it is reasonable to hypothesize that a greater degree of tinnitus may be associated with worse auditory perception, including worse speech reception and worse sound localization. Because unilateral tinnitus severity following sudden sensorineural hearing loss decreases over time in select SSD patients, and because SSD patients may adapt to the loss of binaural cues over time, we hypothesized that SSD subjects would demonstrate better sound-source localization with an increasing duration of deafness.

Materials and Methods

Participants

The study and the informed consent procedures were approved by the institutional review board (Ethics Committee of Eye and Ear, Nose, Throat Hospital of Fudan University, approval number: KY2012-009), and written informed consent was obtained from all participants. Twenty-six SSD subjects (15 male and 11 female) and 10 NH listeners (5 male and 5 female) were recruited to participate in a prospective fashion at a tertiary referral medical center, and air conduction pure tone thresholds were measured for each ear at 0.125, 0.25, 0.5, 1.0, 2.0, 4.0, and 8.0 kHz. Inclusion criteria for the SSD group included a pure-tone average (PTA) threshold, calculated using 0.5, 1.0, and 2.0 kHz, of $\leqslant 30$ dB HL in the NH ear and $\geqslant 70$ dB HL in the worse-hearing ear. In 4 of 26 SSD subjects, the PTA in the better ear was greater than or equal to 25.0 dB. The comparison NH group demonstrated PTA $\leqslant 25$ dB HL bilaterally. Mean age at testing was 31.1 ± 12.0 years (range $= 15$–55 years) for the SSD group and 26.7 ± 2.0 years for the NH comparison group. Mean duration of hearing loss was 7.8 ± 9.7 years (range $= 3$ days to 36 years). Subjects were dichotomized into "short" and "long" durations of deafness, corresponding to <1 year and >2 years, respectively. This threshold was

specifically selected because most patients with a duration of SSD of less than 1 year are subjectively still adapting to their deficits, while by the 2-year mark, many patients have demonstrated significant accommodation in home and work settings to account for their deficits. Table 1 presents the demographic information of the SSD group. Figure 1 shows hearing thresholds for SSD subjects, demonstrating both the better hearing (BH) ear and deaf ear.

Sound-Source Localization

For both SSD and NH subjects, localization was measured in the sound field using stimuli and methods similar to Chan et al. (2008). Loudspeakers were at ear level and spaced 15° apart behind the subject, 1 meter from the center of the subject's head. The stimulus was a broadband impulse sound (a gunshot) presented at 65 dBA; the presentation level was randomly varied over a range of 6 dB (i.e., ±3 dB) to reduce the availability of loudness cues for localization. Prior to formal testing in each condition, subjects were given a preview of the auditory stimulus from each of 12 sound-source locations in order. During testing, a sound source (loudspeaker) was randomly selected, and the stimulus was delivered from that source. The subject responded by clicking on one of the loudspeakers shown on a computer screen that represented the speaker locations, after which a new stimulus was presented. Each subject was instructed not to move his or her head during testing. Stimuli were presented twice from each sound source (24 trials in each test block). Localization accuracy was quantified in terms of root mean square error (RMSE), which was calculated according to the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(AT_i - AR_i)^2}{N}}$$

Table 1. Subject Demographic Information.

Subjects	Age at test	Gender	Duration of deafness (years)	THI	VAS	Deaf ear	Etiology	PTA (dB HL; DEAF ear)	PTA (dB HL; BH ear)
S1	24	M	0.01	50	5	R	Sudden	93.33	13.33
S2	21	M	0.07	—	—	L	Unknown	101.67	15.00
S3	27	F	0.12	40	4	R	Sudden	80.00	11.67
S4	44	M	0.18	46	5	R	Trauma	120.10	21.67
S5	37	M	0.18	56	6	R	Sudden	75.00	15.00
S6	54	M	0.26	42	6	R	Sudden	80.00	13.33
S7	36	M	0.30	18	3	L	Sudden	86.67	13.33
S8	42	F	0.75	56	6	L	Sudden	90.00	25.00
S9	16	F	0.82	—	—	L	Unknown	101.67	16.67
S10	42	F	0.89	38	6	L	Sudden	88.33	15.00
S11	51	M	2.45	—	—	R	Sudden	113.33	26.67
S12	29	F	3.00	—	—	R	Cochlear nerve dysplasia	120.10	18.33
S13	31	F	3.01	72	8	R	Trauma	120.10	20.00
S14	16	M	5.00	—	—	L	Mumps	83.33	16.67
S15	32	F	5.90	26	4	R	Otitis media	118.37	18.33
S16	16	M	7.00	28	3	R	Unknown	93.33	25.00
S17	27	M	8.00	—	—	R	Unknown	110.00	15.00
S18	37	F	10.00	—	—	L	Sudden	120.10	15.00
S19	15	F	10.00	—	—	L	Middle ear cholesteatoma	118.37	8.33
S20	31	M	10.00	44	6	R	Unknown	111.67	26.67
S21	16	F	12.00	—	—	L	Unknown	116.70	15.00
S22	15	M	15.42	—	—	R	Mumps	120.10	13.33
S23	51	M	20.00	54	7	R	Rubella virus	120.10	15.00
S24	20	M	20.24	—	—	R	Unknown	120.10	16.67
S25	30	F	30.32	—	—	L	Cochlear nerve dysplasia	91.67	13.33
S26	36	M	36.21	30	4	R	Unknown	110.00	15.00

Note. THI = Tinnitus Handicap Inventory; VAS = visual analog scale; PTA = pure-tone average; BH = better hearing.
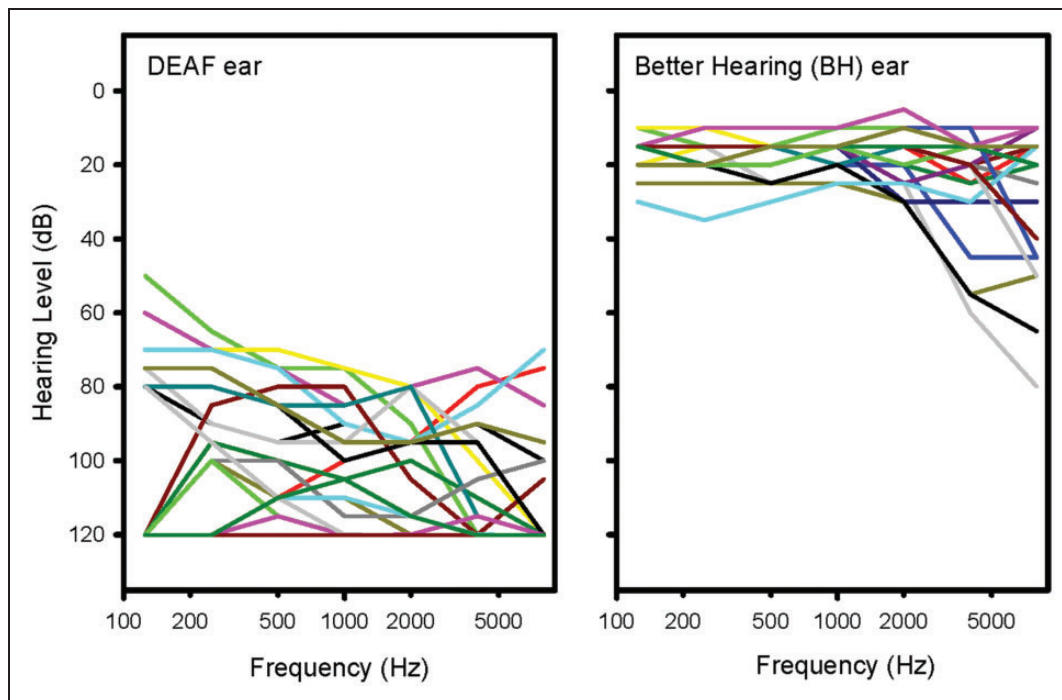
Figure 1. Hearing thresholds for single-sided deafness subjects, demonstrating both the better hearing (BH) ear and deaf ear.

where N is the number of trials (24), i is the individual trial number, AT is the angle in degrees relative to the target speaker location, and AR is the angle in degrees relative to the speaker location selected by the subject. All subjects were tested twice or more with the exception of one subject, who was only tested once due to time constraints.

Speech Recognition in Noise

For both SSD and NH subjects, speech understanding in noise was measured in the sound field with and without spatial cues. Speech (S) was always presented directly in front of the listener. For SSD subjects, noise (N) was either presented to the deaf ear at an azimuth of 90° (S_0N_{DEAF}), in front of the listener (S_0N_0), or to the BH ear at an azimuth of 90° (S_0N_{BH}). For NH subjects, noise was presented to the left ear at an azimuth of 90° (S_0N_{LEFT}), in front of the listener (S_0N_0), or to the right ear at an azimuth of 90° (S_0N_{RIGHT}). Speech reception thresholds (SRTs), defined as the signal-to-noise ratio (SNR) producing 50% recognition of words in sentences (Plomp & Mimpen, 1979), were adaptively measured using Rule 3 from Chan et al. (2008), in which scoring was based on keywords instead of sentences. For keyword-based scoring, a response was designated as correct if more than 50% of keywords were correctly recognized; for sentence-based scoring, a response was designated as correct if all keywords (or the whole sentence) were correctly recognized.

SRTs were adaptively measured by adjusting the noise level according to the correctness of the response. During each test run, a sentence was randomly selected (without replacement) from the 20-sentence stimulus set and presented from the front speaker at 65 dBA; noise was presented at the target SNR to one of the three loud-speakers, depending on the spatial condition. The initial target SNR was 0 dB for all the listening conditions. If the subject repeated 50% or more of words correctly, the noise level was increased by 2 dB; if the subject repeated fewer than 50% of words correctly, the noise level was reduced by 2 dB. The final six reversals in SNR were averaged as the SRT. Speech materials consisted of the Mandarin speech perception sentences produced by a professional single female talker (Fu, Zhu, & Wang, 2011; Li, Wang, Su, Galvin, & Fu, 2017); speech-shaped steady-state noise was employed, filtered to match the spectrum across all Mandarin speech perception sentences.

Tinnitus Severity

Tinnitus severity was measured using a visual analog scale (VAS). Subjects were asked to mark tinnitus severity on a 10-cm line anchored with the extreme labels *No tinnitus at all* corresponding to a score of 0 and *Worst tinnitus imaginable* corresponding to a score of 10. Based on this response, subjects were then stratified into "without tinnitus" (VAS 0) and "with tinnitus" (VAS 1 through 10) categories. In addition to a VAS, the

Tinnitus Handicap Inventory (THI) was also administrated in each subject (Newman, Jacobson, & Spitzer, 1996). The THI is a validated subjective self-administered test that aims to determine the degree of distress suffered by the tinnitus patient. It consists of 25 questions divided into 3 subgroups: functional, emotional, and catastrophic. Eleven items are included in the functional scale, 9 in the emotional scale, and 5 in the catastrophic scale. A score of 100 indicates maximum tinnitus severity and impact, and a score of 0 indicates no tinnitus.

Statistical Analyses

Speech recognition in noise (S_0N_{DEAF}/S_0N_{LEFT}, S_0N_0, $S0N_{BH}/S0N_{RIGHT}$) and sound-source localization were analyzed using one-way analysis of variance (ANOVA). Several variables were used as the independent variable in analyses, including subject groups (NH, SSD); presence of tinnitus (with, without); and duration of deafness (short, long). Tinnitus severity (THI, VAS), duration of deafness, and mean hearing thresholds across all tested frequencies in the SSD and BH ear were compared with sound-source localization and speech recognition in noise (S_0N_{DEAF}, S_0N_0, S_0N_{BH}) using Pearson correlation analyses. The significance level was adjusted after Bonferroni adjustment for multiple comparisons.

Results

SSD Subjects Versus NH Controls

Sound-source localization and sentence recognition in noise at three spatial listening conditions were measured in 26 SSD subjects and 10 NH controls. Figure 2 shows boxplots of sound localization and sentence recognition in noise for both the NH listeners and the SSD subjects. For sound localization, mean RMSE was $12.4° \pm 2.4°$ and $45.1° \pm 12.8°$ for both the NH listeners and the SSD subjects, respectively. A one-way ANOVA was performed with subject groups (NH, SSD) as the independent variable. Mean RMSE was significantly worse in SSD subjects than NH listeners, $F(1, 34) = 63.16$, $p < .001$; $\eta^2 = 0.650$. For speech recognition in noise, mean SRTs were significantly poorer in SSD subjects than NH listeners for all three spatial conditions: S_0N_{DEAF}, $F(1, 34) = 31.64$, $p < .001$; $\eta^2 = 0.482$; S_0N_0, $F(1, 34) = 43.76$, $p < .001$; $\eta^2 = 0.563$; and S_0N_{BH} condition, $F(1, 34) = 136.41$, $p < .001$; $\eta^2 = 0.800$.

With Tinnitus Versus Without Tinnitus

To understand whether *the presence or absence* of tinnitus affects sound-source localization and speech recognition in noise, SSD subjects were further dichotomized into "with tinnitus" (VAS 1 through 10) and "without tinnitus" (VAS 0) groups according to the VAS scores. Figure 3 shows boxplots of sound-source localization and sentence recognition in noise in SSD subjects with tinnitus ($N = 14$) and without tinnitus ($N = 12$). For sound-source localization, mean RMSE was $50.5° \pm 13.5°$ and $38.7° \pm 8.7°$ for those with tinnitus and without tinnitus, respectively. A one-way ANOVA was performed with presence of tinnitus (with tinnitus, without tinnitus) as the independent variable. Mean RMSE was significantly worse in SSD subjects with tinnitus than without tinnitus, $F(1, 24) = 6.72$, $p = .016$; $\eta^2 = 0.219$. For speech recognition in noise, mean SRTs were significantly poorer in SSD subjects with tinnitus than without tinnitus for S_0N_{DEAF} condition, $F(1, 24) = 4.74$, $p = .040$; $\eta^2 = 0.165$, and S_0N_0 condition, $F(1, 24) = 6.10$, $p = .034$; $\eta^2 = 0.173$. However, in the S_0N_{BH} condition, the mean SRT in SSD subjects with tinnitus was similar to that in SSD subjects without tinnitus, $F(1, 24) = 0.314$, $p = .580$; $\eta^2 = 0.013$.

Short Versus Long Duration of Deafness

SSD subjects were also dichotomized into "short" and "long" durations of deafness, corresponding to <1 year and >2 years, respectively. Figure 4 shows boxplots of sound-source localization and sentence recognition in noise in SSD subjects with short (<1 year; $N = 10$) and long (>2 year; $N = 16$) duration of deafness. For sound-source localization, mean RMSE was $55.9° \pm 11.2°$ and $38.3° \pm 8.4°$ for SSD subjects with short and long duration of deafness, respectively. A one-way ANOVA was performed with duration of deafness (short, long) as the independent variable. Mean RMSE was significantly worse for SSD subjects who lost their hearing within 1 year than for SSD subjects who lost their hearing for greater than 2 years, $F(1, 24) = 20.78$, $p < .001$; $\eta^2 = 0.464$. For speech recognition in noise, there was no significant difference in the mean SRTs between short and long duration of deafness for the S_0N_{DEAF} condition, $F(1, 24) = 0.797$, $p = .381$; $\eta^2 = 0.032$; the S_0N_0 condition, $F(1, 24) = 0.748$, $p = .396$; $\eta^2 = 0.03$; and the S_0N_{BH} condition, $F(1, 24) = 0.002$, $p = .966$; $\eta^2 = 0.000$.

Pearson Correlation Analyses

For speech recognition in noise and sound-source localization measures, SRTs among different spatial listening conditions were highly correlated ($p < .001$ in all cases), but there were no significant correlations between sound-source localization and speech recognition in noise at different spatial listening conditions ($p > .05$ in all cases). For tinnitus severity measures, VAS and THI
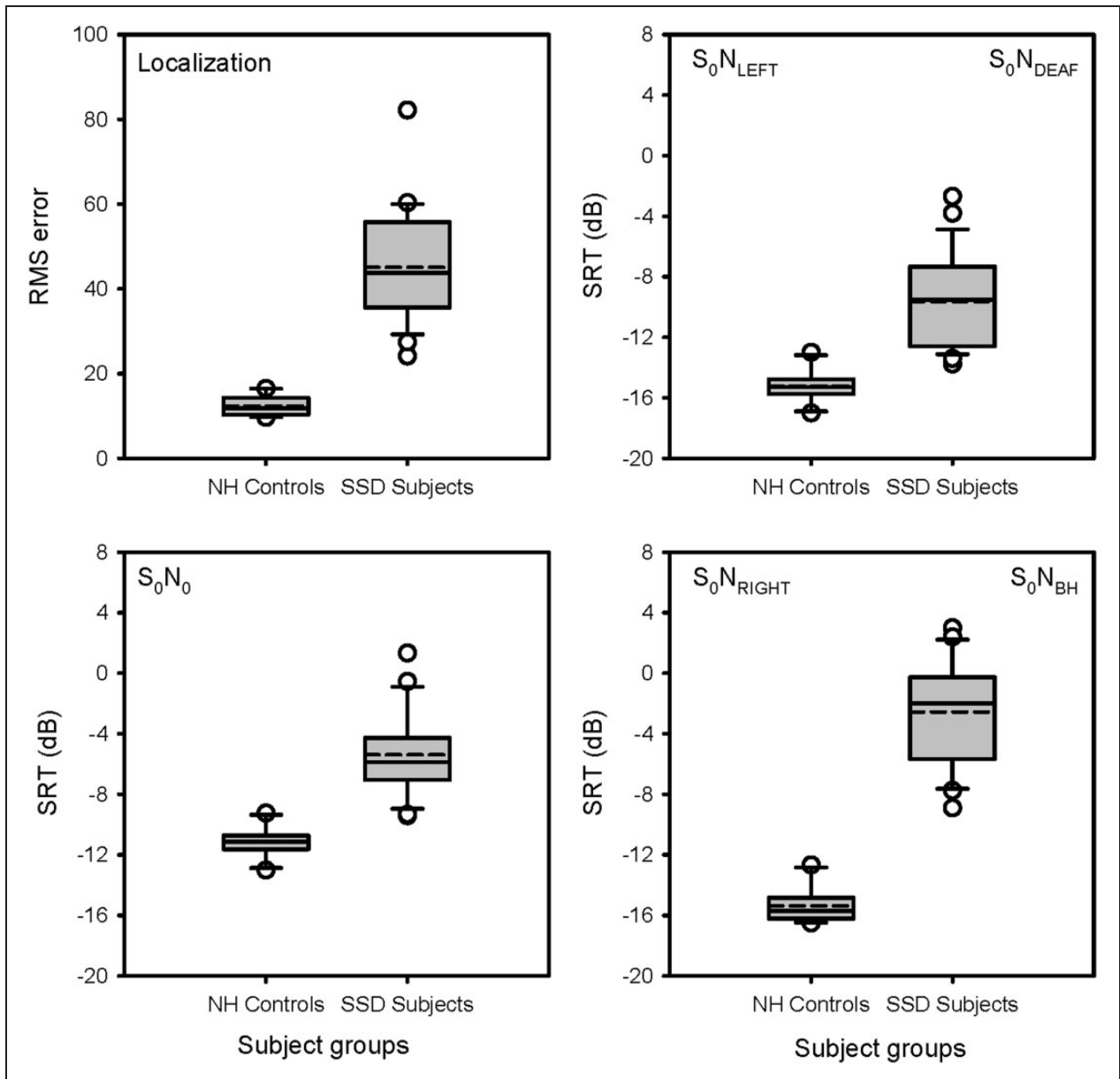
Figure 2. Boxplots of localization RMSE scores and SRTs in noise for the different spatial conditions as a function of subject groups (NH controls and SSD subjects). Top left, RMSE. Top right, SRTs for S_0N_{DEAF} condition. Bottom left, SRT for S_0N_0 condition. Bottom right, SRT for S_0N_{BH} condition. Boxes represent 25th and 75th percentiles, error bars represent 5th and 95th percentiles, circles denote outliers, solid lines show the median, and dashed lines show the mean.
RMSE = root mean square error; SRT = speech reception threshold; NH = normal-hearing; SSD = single-sided deafness.

scores were highly correlated when all SSD subjects ($N = 26$) were included in the Pearson correlation analyses ($r = .979$, $p < .001$). For the 14 SSD subjects who reported having tinnitus, Pearson correlation analyses also showed a highly significant correlation between VAS and THI scores ($r = .879$, $p < .001$).

To better understand the association between tinnitus severity/duration of deafness and sound-source localization/speech recognition in noise, tinnitus severity (THI, VAS), duration of deafness, and mean hearing thresholds across all tested frequencies in the deaf ear and BH ear were compared with sound-source localization and speech recognition in noise (S_0N_{DEAF}, S_0N_0, S_0N_{BH}). Figure 5 shows RMS error (first column) and SRTs as a function of THI scores (first row), VAS scores (second row), duration of deafness (third row), mean hearing thresholds at the BH ear (fourth row) and deaf ear (fifth row) for the three spatial listening conditions: S_0N_{DEAF}
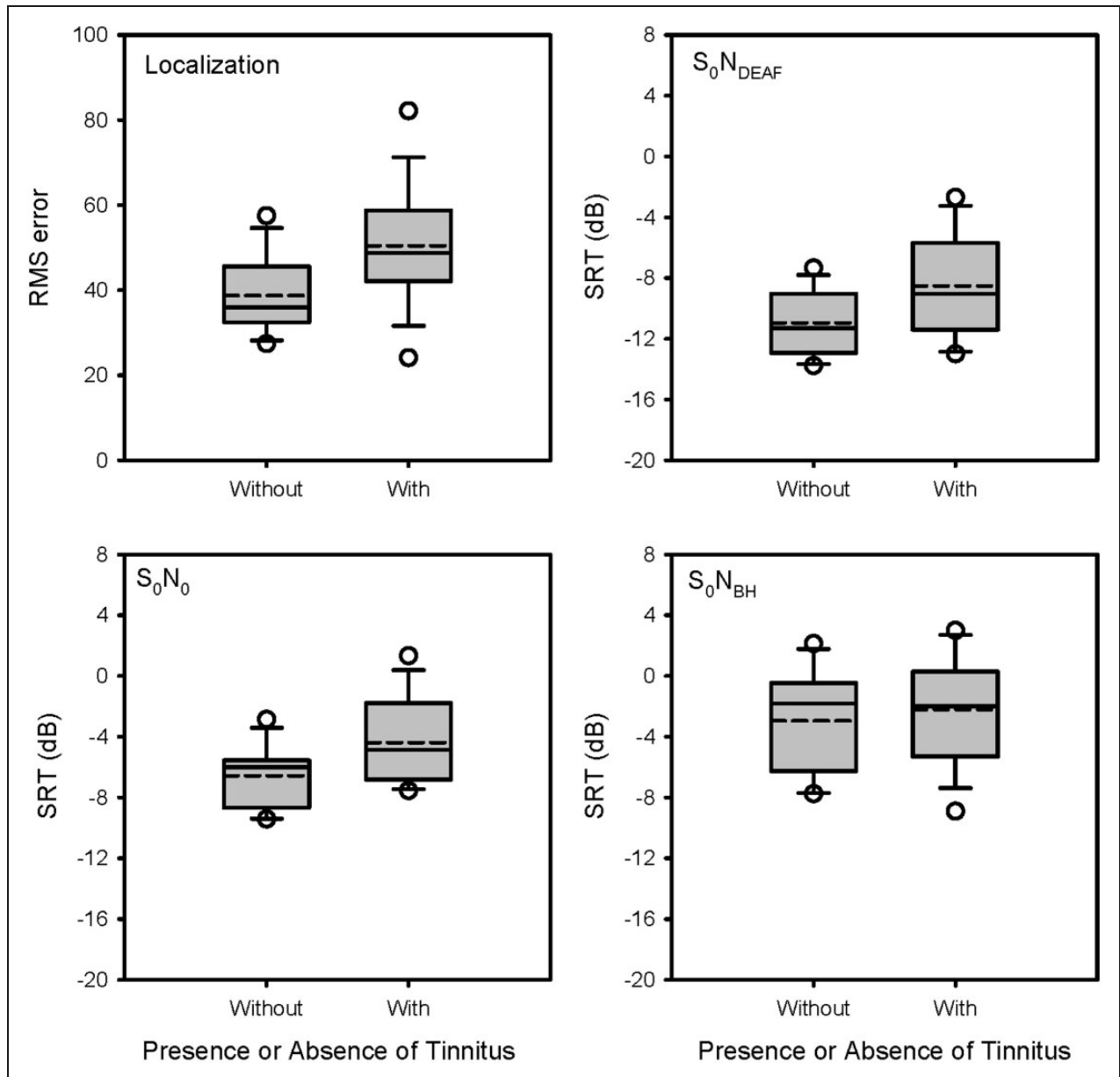
Figure 3. Boxplots of localization RMSE scores and SRTs in noise for the different spatial conditions as a function of the presence or absence of tinnitus in SSD subjects. Top left, RMSE. Top right, SRTs for S_0N_{DEAF} condition. Bottom left, SRT for S_0N_0 condition. Bottom right, SRT for S_0N_{BH} condition. Boxes represent 25th and 75th percentiles, error bars represent 5th and 95th percentiles, circles denote outliers, solid lines show the median, and dashed lines show the mean.
RMSE = root mean square error; SRT = speech reception thresholds.

condition (second column), S_0N_0 condition (third column), and S_0N_{BH} condition (fourth column).

For sound-source localization, RMS errors were positively correlated with tinnitus severity measured by either THI ($r = .530$, $p = .005$) or VAS ($r = .567$, $p = .003$) and negatively correlated with duration of deafness ($r = -.499$, $p = .009$). However, no significant correlations were observed between sound-source localization and mean hearing thresholds of either the deaf ear or the BH ear ($p > .05$). For speech recognition in

noise, significant correlations between SRTs and mean hearing thresholds of the BH ear were observed at all listening conditions ($p < .001$ in all cases). However, there was no significant correlation between SRTs and mean hearing thresholds of the deaf ear at all listening conditions ($p > .05$ in all cases). Some positive correlations were observed between tinnitus severity and S_0N_{DEAF}/S_0N_0 conditions but failed to reach significance level after Bonferroni adjustment for multiple comparisons.
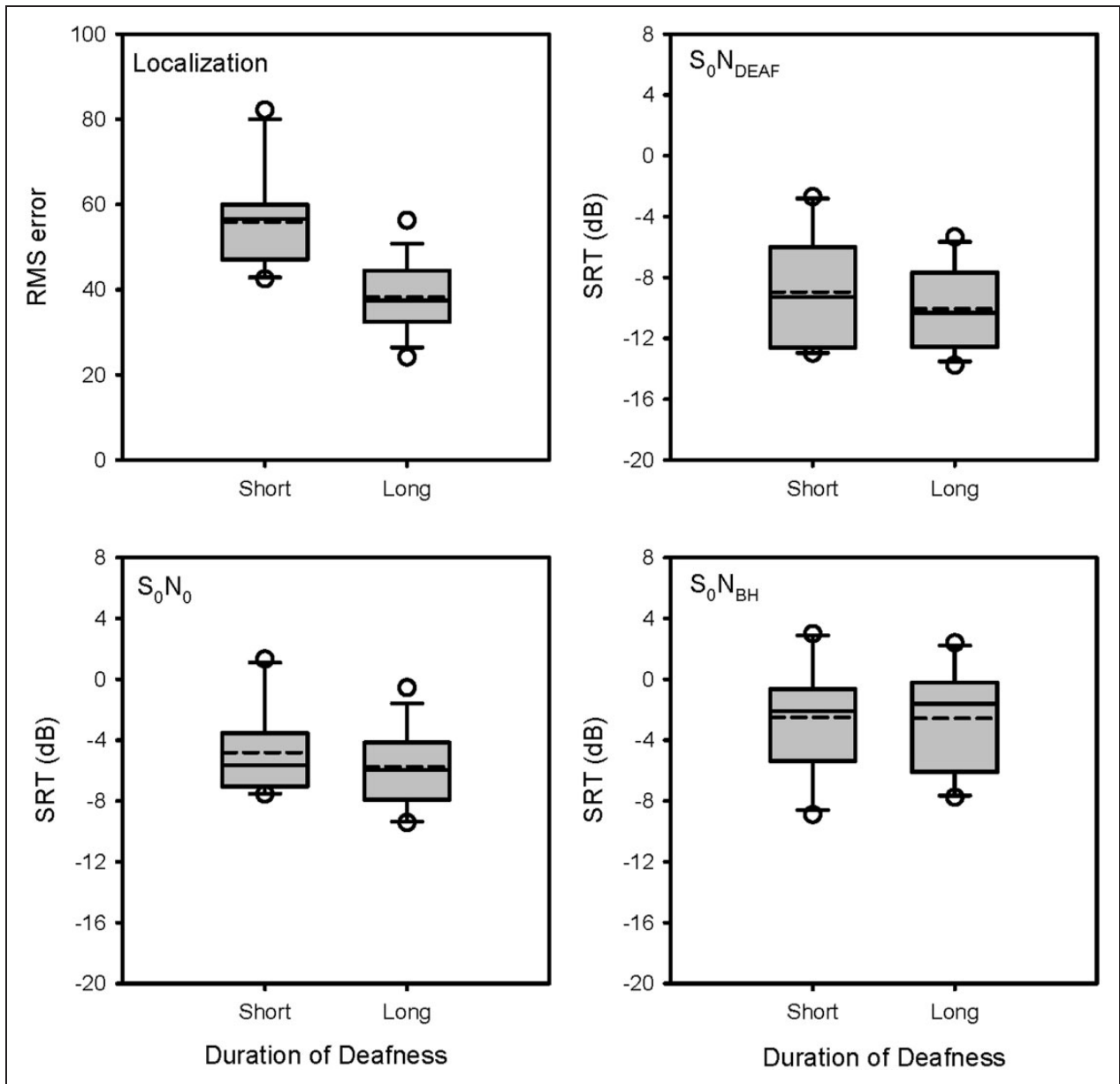
Figure 4. Boxplots of localization RMSE scores and SRTs in noise for the different spatial conditions in SSD subjects with "short" (<1 year) or "long" (>2 years) duration of deafness. Top left, RMSE. Top right, SRTs for S_0N_{DEAF} condition. Bottom left, SRT for S_0N_0 condition. Bottom right, SRT for S_0N_{BH} condition. Boxes represent 25th and 75th percentiles, error bars represent 5th and 95th percentiles, circles denote outliers, solid lines show the median, and dashed lines show the mean. RMSE = root mean square error; SRT = speech reception threshold.

Discussion

In this study, subjects with SSD demonstrated significant deficits in sound-source localization and speech recognition in noise when compared with NH listeners, consistent with previous findings in the literature (Arndt et al., 2011; Buechner et al., 2010; Jacob et al., 2011; Van de Heyning et al., 2008; Vermeire & Van de Heyning, 2009). In addition, we found that sound-source localization was significantly correlated with tinnitus as well as duration

of deafness; speech recognition in noise was also affected by tinnitus.

Tinnitus and Auditory Perception

A majority of SSD patients (54%–84%) have debilitating tinnitus, which can negatively impact daily living (Quaranta et al., 2004; Wie et al., 2010). Most CI studies demonstrate positive results in reducing tinnitus severity in SSD patients (Arts, George,
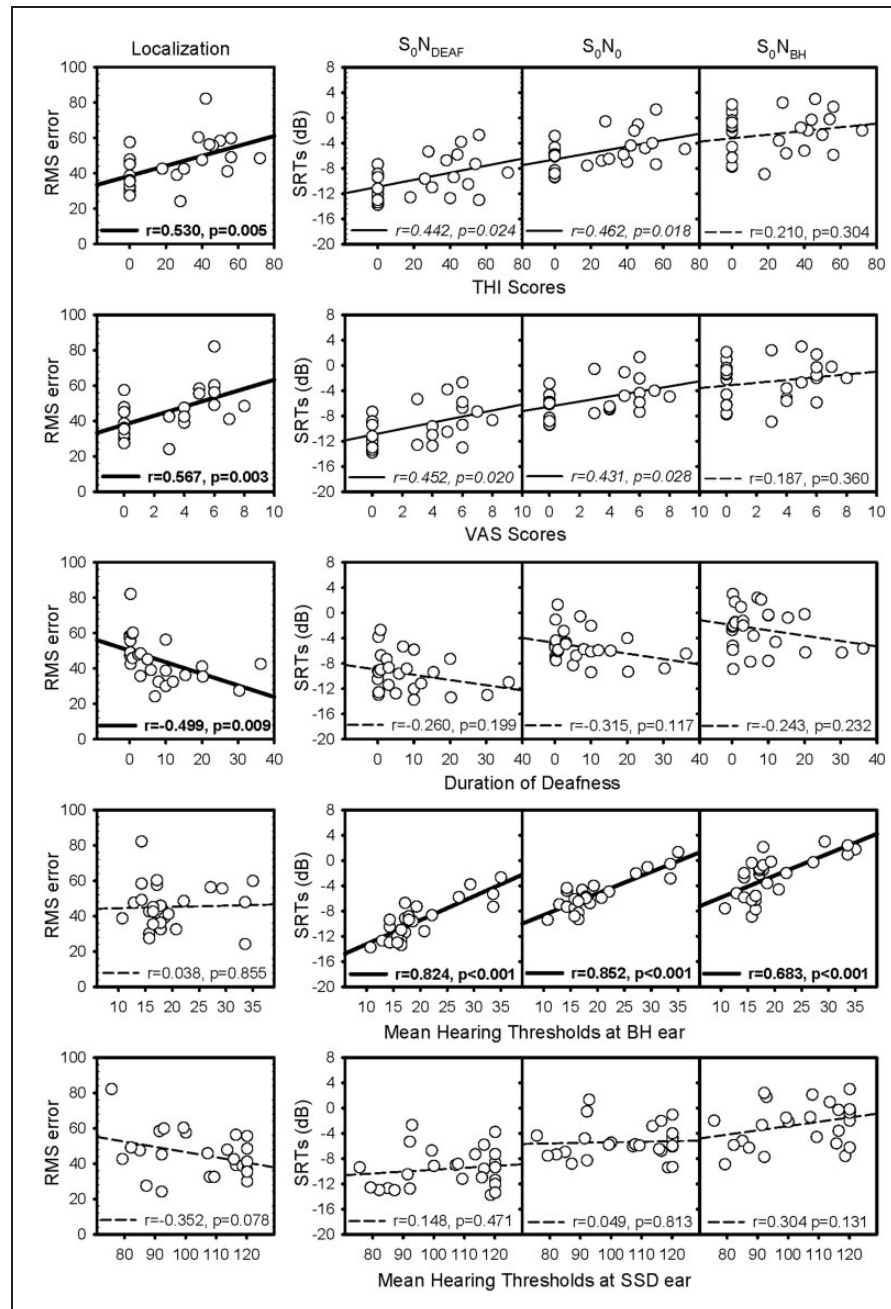
Figure 5. RMS error (first column) and SRTs in noise for the different spatial conditions (S₀N_SSD: second column; S₀N₀: third column; S₀N_BH: fourth column) as a function of THI scores (first row), VAS scores (second row), duration of deafness (third row), mean thresholds of the BH ear (fourth row), or deaf ear (fifth row). Open circles denote the individual data points, while the lines show the linear regression. The correlational coefficients and significance level were also displayed in each panel.
RMS = root mean square; SRT = speech reception threshold; THI = Tinnitus Handicap Inventory; VAS = visual analog scale; BH = better hearing; SSD = single-sided deafness.

Stokroos, & Vermeire, 2012; Cadieux, Firszt, & Reeder, 2013; Dillon et al., 2017; Finke, Strauss-Schier, Kludt, Buchner, & Illg, 2017; Firszt, Holden, Reeder, Waltzman, & Arndt, 2012; Grossmann et al., 2016; Kitoh et al., 2016; Mertens, De Bodt, & Van de Heyning, 2017; Mertens, Kleine Punte, De Bodt, & Van de Heyning, 2015; Nawaz, McNeill, & Greenberg, 2014; Rahne & Plontke, 2016; Tavora-Vieira, De Ceulaer, Govaerts, & Rajan, 2015; Tokita, Dunn, & Hansen, 2014; Van de Heyning et al., 2008; Vermeire & Van de Heyning, 2009; Zeitler et al., 2015). Indeed, one of the first indications for cochlear implantation in

SSD patients was tinnitus and the reduction of its severity (Van de Heyning et al., 2008). In the present study, 14 out of 26 SSD subjects (54%) had noticeable tinnitus. For these 14 listeners, tinnitus severity, measured by VAS, was highly correlated with THI questionnaires, as similarly reported in the literature (Figueiredo, Azevedo, & Oliveira Pde, 2009).

Tinnitus associated with SSD has been demonstrated to correlate with speech recognition in the BH ear (Mertens et al., 2013). For example, Mertens et al. (2013) reported better speech recognition in noise in the BH ear (via insert earphone) when the loudness of tinnitus in the deaf ear was reduced by turning on the external CI processor in the deaf ear without any acoustic signal to the CI processor. The data from the present study showed significantly poorer performance in SSD subjects with tinnitus than subjects without tinnitus when noise was presented to the front or the deaf ear, analogous to the findings of Mertens et al. (2013). The performance deficit due to tinnitus was also dependent on the spatial condition. The largest difference (2.4 dB) was observed when noise was presented to the deaf ear, and the smallest difference (0.7 dB) was observed when noise was presented to the NH ear. Positive correlations were also observed between tinnitus severity (either measured by VAS or THI) and speech recognition in noise at two spatial listening conditions (S_0N_0, S_0N_{DEAF}).

However, the effects of tinnitus on sound-source localization have not yet been explicitly demonstrated in the literature. A prominent finding in the present research is the observation that tinnitus is negatively correlated with sound-source localization. The mean RMSE ($50.5°$) for SSD subjects with tinnitus was significantly poorer than that for SSD subjects without tinnitus ($38.8°$). The correlational analysis also confirmed a significant correlation between sound-source localization and the tinnitus severity measured by either THI ($p = .005$) or VAS ($p = .003$). Because most CI studies demonstrate positive results in reducing tinnitus severity in SSD patients (Van de Heyning et al., 2008; Vermeire & Van de Heyning, 2009), these results from the present study suggested that cochlear implantation may not only provide the binaural cues necessary for sound localization and speech recognition in noise but may also improve the sound localization and speech recognition in noise by reducing tinnitus, potentially through central pathways. This lends credence to the thought that SSD patients with tinnitus may benefit more from cochlear implantation than SSD patients without tinnitus.

It must be emphasized that any inverse correlation observed between severity of tinnitus and auditory performance may be secondary to other effects not investigated or measured by the current work. For example, worse subjective tinnitus may reflect a relatively higher degree of auditory degradation, irrespective of PTA results or duration of deafness, and this underlying auditory degradation may in fact be the predominant cause of poor auditory performance.

Duration of Deafness and Auditory Perception

In the present study, 10 out of 26 subjects had a relatively short duration of deafness (<1 year). Interestingly, 8 out of 10 SSD subjects (80%) with short duration of deafness (<1 year) have tinnitus while only 6 out of 16 SSD subjects (38%) with long (>2 years) duration of deafness have tinnitus. This may suggest that tinnitus is more prevalent in the short term in SSD patients. The trend is consistent with the observation that unilateral tinnitus severity following sudden sensorineural hearing loss likely decreases over time in a subset of patients even if left untreated (Muhlmeier et al., 2016). The mean RMSE was $38°$ for subjects with a longer duration of deafness (>2 years), which was significantly better than subjects with a shorter duration of deafness (<1 year), whose mean was $56°$. Correlational analysis also showed a significant correlation between sound-source localization and duration of deafness ($p = .009$). The longer the duration of deafness, the better the sound-source localization. Two factors may contribute to the improvement over time for sound-source localization. One factor is that, over time, SSD patients adapt to compensate for the loss of hearing by using other cues for sound localization. This is supported by studies that have demonstrated that SSD patients may adapt to the loss of binaural cues over time via the remediation of both spatial and temporal central auditory processing (Chang et al., 2016), and sound localization with one hearing ear may be improved by active lateralization training (Firszt, Reeder, Dwyer, Burton, & Holden, 2015; Yu et al., 2018). The second factor is the reduction in tinnitus severity for SSD subjects with a longer duration of deafness. As mentioned earlier, a significant correlation was observed between tinnitus severity and sound-source localization, suggesting that better sound-source localization may be associated with reduced tinnitus severity in SSD subjects with longer duration of deafness.

Performance Deficits in SSD Subjects Comparing With NH Listeners

Previous studies have revealed significant deficits in sound localization and speech recognition in noise in SSD patients compared with NH controls (Agterberg, Hol, Van Wanrooij, Van Opstal, & Snik, 2014; Arndt et al., 2011; Buechner et al., 2010; Jacob et al., 2011; Van de Heyning et al., 2008; Vermeire & Van de Heyning, 2009). However, it has also been shown that SSD patients demonstrate variable sound localization abilities, with some SSD patients demonstrating excellent

sound localization (Rothpletz, Wightman, & Kistler, 2012). In the present study, NH listeners scored significantly better than SSD subjects in localizing sound (12.4° vs. 45.1° RMSE). Mean RMSE in our SSD subjects population was consistent with data in other SSD subjects who participated in cochlear implantation clinical trials (Galvin et al., 2018). Despite this statistical significance, it is interesting to note that there was significant intersubject variability of sound localization in SSD subjects, ranging from 24.1° to 82.2°.

In SSD subjects, speech recognition in noise depended heavily on the spatial configuration of the noise source. When noise was presented to the deaf ear, SRTs were about 5.6 dB worse in SSD subjects compared with NH listeners. Similarly, a 5.8 dB deficit was observed in SSD subjects when noise was presented to the front. The difference (5.8 dB) between NH listeners (two NH ears) and SSD subjects in the present study was significantly larger than that between monaural listening (simulated SSD by presenting speech and noise to one NH ear only) and binaural listening in NH listeners in a previous study (Zhou, Li, Galvin, Fu, & Yuan, 2017) using the same testing materials (estimated at 1.4 dB). Such a discrepancy could potentially be explained by any impairment of hearing in the better-hearing ear in SSD subjects in the present study. Indeed, Figure 5 showed a significant correlation between speech recognition in noise and mean hearing thresholds at the BH ear for all the spatial listening condition, suggesting that speech recognition in noise may be driven by the hearing thresholds in the BH ear. A similar phenomenon was observed in previous studies (Agterberg et al., 2014; Firszt et al., 2015), in which localization performance in subjects with SSD depended greatly on high-frequency hearing in the BH ear. Localization may improve over time and may also be aided by localization training of the BH ear (Firszt et al., 2015; Yu et al., 2018).

Clinical Interventions for SSD

Several interventions have been proposed to improve SSD patients' sound localization and speech recognition in noise. Noninvasive interventions include contralateral routing of signal (CROS) hearing amplification, in which a microphone on the deaf side routes the acoustic signal to the contralateral hearing ear, and bone-anchored hearing devices (BAHD), in which a receiver and stimulator implanted on the SSD side stimulates the contralateral hearing ear via bone conduction. Both CROS and BAHD systems improve speech recognition in noise, at least subjectively, especially when speech is presented to the deaf ear (Bosman, Hol, Snik, Mylanus, & Cremers, 2003; Peters, Smit, Stegeman, & Grolman, 2015). However, speech recognition in noise worsens when noise is presented to the deaf ear, due to the loss of head

shadow benefit. Furthermore, binaural cues may be further distorted due to the routing of binaural signal to a single ear, resulting in even poorer sound localization than the unaided condition. Neither the CROS nor the BAHD system is effective for tinnitus relief, as the deaf ear is not stimulated. While some studies have shown a general benefit in SSD patients using the CROS and BAHD systems (Faber, de Wolf, Cremers, Snik, & Hol, 2013), other studies have shown that patient acceptance of the CROS and BAHD is relatively poor (Linstrom, Silverman, & Yu, 2009; Martin et al., 2010; Yuen, Bodmer, Smilsky, Nedzelski, & Chen, 2009).

More recently, CI has been proposed as a surgical intervention for SSD patients. The initial indication for CI in SSD patients was to reduce tinnitus severity (Van de Heyning et al., 2008). The vast majority of studies confirm that CI reduces tinnitus severity (Arts et al., 2012; Cadieux et al., 2013; Dillon et al., 2017; Finke et al., 2017; Firszt et al., 2012; Grossmann et al., 2016; Kitoh et al., 2016; Mertens et al., 2015, 2017; Nawaz et al., 2014; Rahne & Plontke, 2016; Tavora-Vieira et al., 2015; Tokita et al., 2014; Van de Heyning et al., 2008; Vermeire & Van de Heyning, 2009; Zeitler et al., 2015). In addition, previous studies have also shown significant improvement in some other measurements, such as sound localization and speech recognition in noise. However, such benefits are highly variable across studies. The data from the present study showed that sound localization and speech recognition in noise was negatively correlated with tinnitus. The observed improvement in the sound localization and speech recognition in noise in SSD post-CI may be related to the reduction of tinnitus, particularly through changes in central processing, but this does not imply causation. Rather, a significant reduction in tinnitus severity in certain patients following CI for SSD may reflect a greater degree of afferent auditory input regained by these individuals, whose performance may then be demonstrably better than those who receive little, or no, tinnitus benefit from implantation. The data from the present study bring up the question of whether SSD patients with tinnitus may benefit more from CI than those without tinnitus.

The long-term effects of deafness should be carefully considered before recommending CI in SSD patients. As shown in the present study, SSD patients who have longer duration of deafness are more likely to have less tinnitus and better sound localization. Prior research showed that those with earlier age at onset localized better than those with recent onset; however, age at onset did not differentiate the groups for speech understanding in noise (Firszt, Reeder, & Holden, 2017). The better sound localization in our SSD patients with longer duration of deafness is likely explained by adaptation using other cues for sound

localization to compensate for the loss of binaural hearing. The lower incidence of tinnitus in these SSD patients with a longer duration of deafness is also associated with better sound localization, possibly reflecting long-term adaptation. Because tinnitus severity and sound localization may improve once SSD patients adapt to the hearing loss in one ear in the long-term, the relative benefits of CI may diminish with increasing duration of deafness; future criteria for CI in SSD should take this into account.

Conclusion

In the present study, sound localization and speech recognition in noise was evaluated in SSD subjects. Beyond confirming VAS and THI correlation in SSD subjects with tinnitus as well as the significant deficit in SSD subjects with regard to sound localization and speech recognition in noise when compared with NH individuals, we observed that SSD subjects with tinnitus performed more poorly than SSD subjects without tinnitus in localization and recognition in noise. A shorter duration of deafness in SSD subjects was associated with a greater incidence of tinnitus and worse performance in sound localization, and speech recognition in SSD subjects was highly dependent on the mean thresholds of the BH ear.

ORCID iD

Bing Chen   http://orcid.org/0000-0002-0988-9534
Qian-Jie Fu   http://orcid.org/0000-0003-3494-7633

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